NEW PERSPECTIVES ON THE MANAGEMENT OF *HELICOVERPA ZEA* (BODDIE) (LEPIDOPTERA: NOCTUIDAE) IN UNITED STATES SWEET CORN: IMPLICATIONS FOR 21ST CENTURY PRODUCTION AND INTEGRATED PEST MANAGEMENT PRACTICES

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ABSTRACT

Helicoverpa zea (Boddie), the corn earworm, is a polyphagous caterpillar pest found throughout the United States and is a key pest of sweet corn. Chapter one is a review of literature relevant to the biology, ecology and management of *H. zea* in United States sweet corn production. Chapter two evaluates the predictive ability of male moth pheromone trap catch alone compared to a model that incorporates multiple factors on the biology and development of *H. zea* and the environment. Chapter three tests the efficacy of insecticides, registered for use against *H. zea* in sweet corn, in context to important timing windows during sweet corn ear development, as outlined in chapter two. The epilogue summarizes conclusions and identifies areas of future research.

Chapter one is a comprehensive review of the literature relating to the biology, ecology and management of *H. zea* in United States sweet corn production. First, *H. zea* behavior, development, host interactions and ecology are reviewed, including host range, dispersal and migration, diapause and overwintering. Next, integrated pest management (IPM) practices for control of *H. zea* are discussed. Then, current tools including cultural, biological, chemical and transgenic controls for *H. zea* are reviewed. Finally, research needs likely to be of importance for management of *H. zea* in coming years are outlined.

Female *H. zea* oviposit on sweet corn silks and yield loss occurs when neonates migrate into the ear under the husk to feed because a single larva can cause complete economic loss if the ear is for fresh market purposes. Chapter two examines current integrated pest management (IPM) guidelines for sweet corn that use pheromone trap-captured male *H. zea* moths to inform management decisions compared to models inclusive of additional factors relevant to ovipositional behavior or development of *H. zea*. Results of logistic regression and predictive

discriminant analyses demonstrate that using multiple environmental and biological factors do, in fact, provide a higher predictive power than pheromone trap catch alone. These results show that IPM strategies to control *H. zea* damage in sweet corn should use multiple biological and environmental factors important for oviposition and infestation, and that pheromone trap catch alone is not the best predictor of damage at harvest.

Chapter three draws on the conclusions of chapter 2, asking whether sweet corn can be protected more effectively if insecticides are applied to target the most attractive silking periods for female *H. zea* oviposition. The relationship between insecticide application timing from tassel through silk stages and marketable yield at harvest were evaluated in the field. Results were compared to yields resulting from current IPM recommendations for the northeast United States. The effectiveness of three registered insecticides (methomyl, chlorantraniliprole and lambda-cyhalothrin), each representing a different class of insecticide, were evaluated. Significant yield differences among insecticides and timing treatments were detected and the combined effects of active ingredient with timing determined the extent of *H. zea* damage. The efficacy of chlorantraniliprole as an effective means of *H. zea* control in sweet corn was unclear. In year 1, there was no significant effect of insecticide type or application timing, but there was a significant interaction effect between factors. In year 2, there was a significant effect of insecticide type. Chlorantraniliprole treatments resulted in significantly higher percentages of sweet corn ears compared to lambda-cyhalothrin. There was also a main effect of application timing. Four insecticide applications made from 50% tassel to 25% dry silk resulted in significantly higher percentages of clean ears at harvest compared with a single insecticide application made at 50% tassel. Compared to other timing treatments, however, there were no significant differences.

The epilogue provides a summary of conclusions reached from chapters one through three. This section also discusses areas of future research that include plant-insect dynamics, chemical ecology and possibilities for advancement of IPM strategies for *H. zea* management in the 21st century.

BIOGRAPHICAL SKETCH

Daniel Olmstead completed his Bachelor of Science in Environmental Science from Nazareth College of Rochester in 1999. From 1999 to 2002, Daniel worked as a Natural Resources Educator for Cornell University Cooperative Extension, in Niagara County, New York State. In 2002, Olmstead accepted a position with the Cornell University Waste Management Institute, in Ithaca NY, where he participated in collaborative soil health and farm composting research projects. In 2005, Daniel came to the Cornell University's New York State Agricultural Experiment Station to do research in the areas of soil insect ecology and turfgrass entomology. In 2010, he accepted a research support position with Dr. Anthony Shelton, also in Geneva NY. In 2012, Daniel was accepted into the Graduate field of Entomology at Cornell University to complete a Master of Science degree under the Employee Degree Program.

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Chapter 1: Management of *Helicoverpa zea* (Boddie) (Lepidoptera: Noctuidae) in United States sweet corn production

Helicoverpa zea (Boddie), the corn earworm, is a polyphagous caterpillar pest (Lepidoptera: Noctuidae) found in the western hemisphere (Cohen et al. 1988, CABI 2014). *H. zea* is an important pest of many horticultural and field crops in North America with a broad host range, but this review focuses on its importance as a pest of sweet corn, *Zea mays* L. convar. *Saccharata* Koern, in the United States (Barber 1943, Phillips and Whitcomb 1962, Coop et al. 1992, 1993, Shelton et al. 2013). The recent decline of another important sweet corn pest, *Ostrinia nubilalis* (Hübner), the European corn borer (Hutchison et al. 2010), has elevated the status of *H. zea* to a primary pest of concern in sweet corn in many parts of the United States. Left unmanaged, *H. zea* causes severe yield reduction and economic loss in sweet corn (Shelton et al. 2013).

The presence of a single insect or its damage renders a sweet corn ear unmarketable for fresh-market production. Sweet corn grown for processing purposes has more tolerance for *H. zea* larvae and damage because they are usually confined to the ear tip, which can be mechanically removed in the processing facility (Shelton 1986). Successful management of *H. zea* is achieved when control strategies target the reproductive silking period when infestation occurs. Effective strategies should use a predictive approach based on adult populations, plant phenological stage, and fast effective preventive control measures to reduce pest numbers.

With the increasing importance of *H.* zea as a pest of sweet corn, it is appropriate to provide a historical and contemporary review of this pest, so that insight can be gained for future management strategies. This review (1) provides background information on sweet corn

production, (2) highlights important aspects of *H. zea* behavior, development and ecology that influence its pest status on sweet corn, (3) reviews contemporary management strategies for *H. zea* in sweet corn, and (4) discusses considerations for future management.

Sweet corn production

Sweet corn is an important specialty crop of global importance grown for fresh-market and processing purposes (Velasco et al. 1999, Santalla et al. 2001, Santos et al. 2003, Chen and Li 2011). In 2013, sweet corn was harvested on >28,000 United States farms in all 50 states, with Minnesota, Washington, Wisconsin, Florida and New York harvesting the largest areas. Florida, California and Georgia are the largest producers of fresh sweet corn, while processing sweet corn is concentrated in the upper Midwest and the Pacific Northwest. Sweet corn adds considerable economic value to the United States agricultural economy and was valued in 2013 at $1.2B (USD). In the same year, 96,591 ha of sweet corn were harvested for fresh market with a value of $842.3M (USD) and a per ha value of $8,720 and 127,510 ha were harvested for processing with a value of $357.8M (USD) and a per ha value of $2,806 (USDA NASS 2014).

There are numerous sweet corn varieties and hybrids, but all utilize specific phenotypic traits that are responsible for its flavor and edibility. Controlled by three genes, these loci include *Su, Se* and *Sh-2*. *Su* causes the pericarp to produce water-soluble polysaccharides instead of starches and results in the desirable eating characteristics (James et al. 1995, Tracy et al. 2006). *Se*, when activated, enhances the activity of *Su* causing the production of additional sugars (Ferguson et al. 1978). Homozygous *Sh-2* varieties produce kernels with higher sugar content than *Su* homozygous varieties (Laughnan 1953, Najeeb et al. 2011) .

Corn with desirable traits for human consumption was grown in the Americas prior to European settlement (Wilkinson 1915, Huelsen 1954, Tracy et al. 2006). In 2006, genetic analysis revealed that modern lines came from progenitors in the northeast US, but that desirable eating traits coevolved in other regions including Peru, Mexico, and the southwestern and north central United States (Tracy et al. 2006). The earliest post-European record of sweet corn was made in 1779 at Plymouth, MA (northeastern US) when military expeditions returned from the Susquehanna River and Genesee Valley regions of the northeast US. Native Americans of the upper Missouri River and Great Plains also grew sweet corn (Wilkinson 1915, Huelsen 1954).

Description and life history of *H. zea* on sweet corn

Description. *H. zea* larvae hatch from eggs laid singly on fresh corn silks. Within hours of hatching, neonates move down the silk and into the developing ear where they are protected from insecticide sprays and natural enemies for the remainder of their development. Once in the ear, larvae proceed through 5 or 6 instars, depending on temperature and time of year. Larvae also exhibit color morphs that vary both among and within individuals depending on instar stage. When caterpillars reach the prepupal stage, they crawl out of the husk and drop to the ground and burrow into the soil. If a caterpillar pupates during the warm summer months, development continues directly to adult eclosion. However, if a caterpillar pupates in the autumn as days shorten and temperatures drop, they will diapause. If diapause occurs in an area with mild winter conditions, adults will eclose the following spring. If conditions are harsh, pupae may experience winter mortality (Hardwick 1965).

Host Range. *H. zea* develops on a variety of other agricultural and wild hosts besides *Z. mays* (field corn) and *Z. mays* convar. *saccharata* (Koern) (sweet corn), which gives rise to many

common names including cotton bollworm, tomato fruitworm, soybean podworm, sorghum headworm and vetchworm (Smith and Bass 1972, Ellsbury et al. 1989, Lingren et al. 1993, Sudbrink and Grant 1995, Blanco et al. 2007, Capinera 2014). Sweet corn and field corn are ideal hosts for *H. zea* larvae (Waldbauer et al. 1984, Cohen et al. 1988) because of their nutritional value and protection within the husk from predators and inclement weather within the ear husk.

H. zea adults and larvae are polyphagous, opportunistic feeders. Adults visit a wide range of plants to obtain energy in the form of nectar or plant saps. Pollen studies show that adults visit plant families such as citrus, oak, rose, willow, aster, and willowherb to nectar feed (Lingren et al. 1993). *H. zea* adults do not feed on sweet corn or field corn because the plants do not produce nectar or possess extra floral nectaries.

Sweet corn is a preferred host for *H. zea* larval development, but successful development can also occur on a wide range of alternate hosts (Neunzig 1963, Hardwick 1965, Sudbrink and Grant 1995, Kennedy and Storer 2000). Alternate hosts to sweet corn in agricultural systems of the United States include beans (*Phaseolus* spp), cotton (*Gossypium* spp), crimson clover (*Trifolium incarnatum*), eggplant (*Solanum melongena*), field corn (*Zea mays*), garbanzo (*Cicer arietinum*), lettuce (*Lactuca sativa*), okra (*Abelmoschus esculentus*), pea (*Pisum sativum*), pepper (*Capsicum* spp), sorghum (*Sorghum* spp), soybean (*Glycine max*), sunflower (*Helianthus* spp), strawberry (*Fragaria* spp), tobacco (*Nicotiana* spp), tomato (*Solanum* spp), vetch (*Vicia* spp) and certain ornamentals (Hardwick 1965, Johnson et al. 1975, Ellsbury et al. 1989, Blanco et al. 2007). Wild host plants able to support *H. zea* development include black medic (*Medicago lupulina*), common mallow (*Malva neglecta*), deergrass (*Rhexia* spp), hophornbeam copperleaf

(*Acalypha ostryaefolia*), hairy galinsoga (*Galinsoga cilliata*), toadflax (*Linaria Canadensis*), and velvetleaf (*Abutilon theophrasti*) (Neunzig 1963, Sudbrink and Grant 1995, Blanco et al. 2007).

The ability of *H. zea* to utilize a wide range of agricultural and wild plant hosts is important to consider for sweet corn management. As the diversity of an agricultural landscape increases, the probability of successful *H. zea* development and subsequent infestation increases as well because the polyphagous nature of *H. zea* allows it to adapt to changes in host availability, both spatially and temporally (Kennedy and Storer 2000).

Dispersal and migration. Infestation of sweet corn by *H. zea* is due, in part, to a dynamic system of population movements by adult moths at local, regional and continental scales (Fitt 1989, Latheef et al. 1993, Westbrook et al. 1997, Gould et al. 2002, Westbrook and Lopez 2010). Landscape-level movements occur when moths seek nectar, search for mates, search for oviposition sites, or require an alternate host (Latheef et al. 1993, Lingren et al. 1993). As previously described, adult *H. zea* sustain their energy levels by nectar feeding, but must do so by visiting flowering plants other than sweet corn. When females are ready to lay eggs, they search for sweet corn plant volatiles (Cantelo and Jacobson 1979, Raina et al. 1992), and when corn has matured and silks are dry, they cease oviposition on that host. (Fitt 1989, Kennedy and Storer 2000).

Although *H. zea* is widespread throughout North America (CABI 2014), their spatial and temporal distribution are variable. *H. zea* populations in the southern United States are endemic (Latheef et al. 1993, Westbrook et al. 1997), while in other regions, populations may be mixed or exclusively migratory (Lingren et al. 1993, Sandstrom 2007). In the southern United States the first generation of *H. zea* completes its development primarily on either cotton or field corn, but then enters a migratory phase to find suitable plant hosts for the next generation, since their

original host crops are no longer available (Hendrix et al. 1987, Wolf et al. 1990, Latheef et al. 1993, Beerwinkle et al. 1994, Westbrook et al. 1997, Gould et al. 2002, Westbrook and Lopez 2010).

Long-range migrations of *H. zea* occur when moths fly to altitudes greater than 200 m, where low-level jet streams can transport moths up to 400 km over several hours (Wolf et al. 1990, Beerwinkle et al. 1994). In the spring, this system results in northward movement and each subsequent generation then utilizes this same mechanism. Each time a new population migrates, movements to more northerly latitudes occur.

After *H. zea* populations migrate to an area, landscape composition and abiotic factors influence flight behavior, oviposition and subsequent establishment in sweet corn (Lopez et al. 1978, Coop et al. 1993, Culin 1995, Lynch, Wiseman, Sumner, et al. 1999, Allen and Luttrell 2006, Storer et al. 2008). In the Midwest US, field corn represents a high proportion of the landscape, followed by soybeans, and both are suitable developmental hosts of *H. zea* (Johnson et al. 1975, Storer et al. 2001, Jackson et al. 2008, USDA NASS 2014). The probability of *H. zea* infestation in a sweet corn field planted within this monoculture is likely to be higher in contrast to the northeast US, where these same plant hosts represent a smaller proportion of the total landscape. Sweet corn planted within a diversified landscape in the Northeastern United States is likely to have a different series of interactions with *H. zea* than in the Midwest US.

Sweet corn as a host. Sweet corn is a preferred host of *H. zea* and results in higher rates of successful development than other hosts (Johnson et al. 1975, Hayes 1988). The developing ear is an ideal source of nutrition for *H. zea* (Cohen et al. 1988). Components of a corn kernel have different nutritive qualities and caterpillars, in turn, can take advantage of those differences to satisfy their developmental requirements (Waldbauer et al. 1984). If corn is present in the

landscape and in an attractive phenological stage, *H. zea* preferentially infests corn (Johnson et al. 1975) because the likelihood of completing its development to the pupal stage is high.

The developmental rate of *H. zea*, like other poikilotherms, is dependent on the temperature of their immediate surroundings (Wagner et al. 1984). Day-degree models have been constructed to estimate development of *H. zea* in sweet corn (Mangat and Apple 1966, Stinner et al. 1974, Butler 1976) and economic loss that occurs as a result of infestations (Butler and Scott 1976, Coop et al. 1993). The lower developmental temperature threshold has been calculated as 12.5°C (54.7°F) for *H. zea* reared on sweet corn (Mangat and Apple 1966). Maximum developmental threshold temperatures for eggs, larvae, pupae and adults are 34°C, 36°C, 35°C and 42°C, respectively (Butler 1976). Mangat and Apple (1966) calculated that 690.2 day-degrees are required from oviposition to 75% adult emergence.

Female *H. zea* moths are attracted to ethylene, one of many volatiles produced by corn silks. After a female detects ethylene, she will produce sex pheromones to attract males (Raina et al. 1991, 1992). Although females can oviposit on any part of the sweet corn stalks or leaves and may do so as early as whorl stage (Barber 1943, Johnson et al. 1975), they prefer to oviposit on silks. A single *H. zea* female can lay from 800 to 1100 eggs in her lifetime (Akkawi and Scott 1984). Past studies have shown that infestation and yield loss from *H. zea* occur only when eggs are laid on corn silk, in contrast to *O. nubilalis* which lays its eggs on leaves and the larvae move to infest the stalks, tillers or ears (Hardwick 1965, Coop et al. 1992).

After hatch, *H. zea* larvae eat the egg corion and then corn silk, then move quickly downward into the husk of a developing ear, which is important for management considerations (Barber 1941), discussed in later sections. Inside the ear, they feed exclusively on corn kernels and do not exit the husk until they prepare for pupation (Waldbauer et al. 1984, Cohen et al.

1988). At the prepupal stage, *H. zea* larvae exit the corn ear, drop to the ground, and burrow 5 to 13 cm into the soil where a pupal cell is constructed (Roach and Hopkins 1979).

Diapause. *H. zea* diapauses in the pupal stage sometimes up to 20 months to avoid adverse conditions (Phillips and Newsom 1966). Photoperiod and temperature have strong effects on the induction of diapause in *H. zea* larvae (Phillips and Newsom 1966, Wellso and Adkisson 1966, Benschoter 1968, Roach and Adkisson 1970). Photoperiods >13 h per day completely suppress the onset of diapause (Benschoter 1968), while photoperiods ≤ to 10 h per day result in maximum diapause rates for *H. zea* larvae (Phillips and Newsom 1966, Benschoter 1968). Diapause induction is maximized when photoperiod is short and temperatures are low (Wellso and Adkisson 1966). However, the effect of a shorter photoperiod on diapause induction can be counteracted if temperatures increase, and a longer photoperiod is counteracted by low temperatures (Phillips and Newsom 1966). If the parent moth of an autumn-maturing *H. zea* larva experiences a longer photoperiod, the likelihood of diapause increases (Wellso and Adkisson 1966, Roach and Adkisson 1970). In contrast, the probability of diapause onset in a larva decreases if the parent moth underwent diapause (Phillips and Newsom 1966).

Overwintering. *H. zea* overwinters in the pupal stage and its ability to successfully overwinter is determined by cold hardiness characteristics including the supercooling point (SCP), lower lethal time (LLtime) and lower lethal temperature (LT50) (Bale 1987, Morey et al. 2012). Pupae that enter diapause survive at significantly lower soil temperatures and have lower SCP than non-diapausing pupae, but non-diapausing pupae held at a constant temperature between 10°C and 20° C for an extended time also have a lower SCP (Eger et al. 1982, Morey et al. 2012).

Abiotic factors that influence pupal overwintering survival include soil moisture, soil type and duration of exposure to low temperatures (Slosser et al. 1975). Direct contact with soil moisture increases pupal mortality at sub-freezing temperatures due to nucleation of water to ice within pupal tissues, where in an otherwise dry environment, antifreeze compounds in the hemolymph would protect the insect (Eger et al. 1982). Higher soil temperatures are also associated with increased pupal mortality due to increased respiration and drowning (Williams and Stinner 1987).

Morey et al. (2012) reported SCP values of -19.3°C and -16.4°C for diapausing and non-diapausing *H. zea* pupae, respectively. LT_{50} values for diapausing and non-diapausing pupae were -13.0°C and -10.0°C, respectively. The difference in time to mortality between diapausing and non-diapausing *H. zea* pupae is significant, with the former surviving many times longer than the latter. For example, at 0°C, time to 50% mortality of non-diapausing pupae is 474 h, while diapausing pupae have a time to 50% mortality of 1,127 h (Morey et al. 2012).

Survival beyond the pupal stage depends on how far north the population has migrated. For example, larvae that complete development on corn and pupate below 40° north latitude have a good chance to survive overwinter. In contrast, larvae that complete development and pupate on corn above 40° are not likely to survive overwinter (Hardwick 1965, Westbrook and Lopez 2010, Morey et al. 2012). This was most recently confirmed when soil temperature profiles were evaluated in Texas, Missouri, Kansas, Iowa, and Minnesota and compared to laboratory derived lethal time (LT_{50}) values (Morey et al. 2012). Soil temperature conditions were lethal in states above the 40° parallel because the period at which pupae were exposed to extreme low temperatures was much greater than the average period experienced among locations below the 40° parallel.

Abiotic mortality factors. Abiotic factors including relative humidity (RH), temperature, moisture, photoperiod and lunar phase influence *H. zea* populations. RH influences the rate of development, pupation rate, pupal weight and adult emergence of *H. zea* (Harrell et al. 1979). Temperature influences mating, larval development, feeding behavior, flight capacity, and diapause induction (Callahan 1958, Mangat and Apple 1966, Phillips and Newsom 1966, Wellso and Adkisson 1966, Eger et al. 1982, Westbrook et al. 1997, Morey et al. 2012). Soil moisture influences pupal survival and adult emergence (Roach and Hopkins 1979, Williams and Stinner 1987). Photoperiod influences diapause induction (Wellso and Adkisson 1966, Roach and Adkisson 1970) and lunar phase influences adult noctuid flight behavior and plant host seeking (Sotthibandhu and Baker 1979, Parajulee et al. 1998).

Biotic factors play an important role in population dynamics as well. A wide variety of natural enemies attack *H. zea*. Mortality can be caused by predation, parasitism, and pathogens (Fitt 1989), all of which are described in sections that follow.

Management

Prevention of sweet corn ear damage is achieved when *H. zea* are intercepted at the egg or early larval stages, before they reach the well-protected husk interior. Damage occurs by larvae that develop from eggs laid on fresh green silks (Barber 1943, Johnson et al. 1975, Flath et al. 1978, Cantelo and Jacobson 1979, Akkawi and Scott 1984, Raina et al. 1992). Current management decisions are based on pest monitoring and use of action thresholds to time insecticide applications (Shelton et al 2014). The economic threshold and economic injury level for *H. zea* larvae in fresh-market sweet corn are the same, i.e. 1 per plant. Sweet corn grown for processing purposes has greater tolerance because ear tips where *H. zea* larvae are almost

exclusively found can be removed. For this reason the economic threshold and economic injury level are higher than that of fresh market, and can be > 1, as long as larvae remain in the ear tip.

Monitoring. Since the late 1980s, *H. zea* adult moth populations have been monitored for management decisions using pheromone traps baited with female sex pheromone blends. These traps are commonly used in IPM programs for *H. zea* in sweet corn (Coop et al. 1992, 1993). When compared side by side to blacklight trap methods, pheromone traps capture male moths in equivalent numbers to female moths flying at the same time (Chowdhury 1987a, Latheef 1993). This relationship serves as the basis for predicting female flight activity, oviposition and subsequent larval damage. Accurate prediction of female oviposition is best calculated when male moths are counted on a single day when insecticide sprays have not been applied (Chowdhury et al. 1987a, 1987b).

The attractiveness of *H. zea* pheromone lures to male moths and the effectiveness of trap types vary significantly. Studies conducted in the early 1990's indicated that the attraction to *H. zea* lure brands varies significantly, due to differences in manufacturing methods. Likewise, trap design varied in efficacy with Hartstack and Heliothis-type traps capturing significantly more moths than other types on the market (Drapek et al. 1990, Gauthier et al. 1991). Lures manufactured to attract male *H. zea* moths also attract other noctuid moths, including yellow-headed cutworm *Apamea amputatrix* (Fitch), false wainscot moth *Leucania pseudargyria* (Guenee), dock rustic moth *Luperina passer* (Geunee), and true armyworm *Pseudaletia unipuncta*, the presence of which can complicate monitoring procedures (Weber and Ferro 1991).

Factors such as sweet corn planting date, frequency of insecticide applications, and pheromone catch have been used in predictive models to understand when and how infestation

by *H. zea* occurs. Chowdhury et al. (1987) found that male pheromone trap counts made on a single insecticide-free day best predicted yield loss at harvest in Georgia. In Texas, modeling of pheromone trap data and other factors revealed a significant association between production of fresh green silks on the ear and corresponding moth flights, followed by oviposition (Latheef et al. 1991).

Pheromone-based control. Two types of chemical communication occur in sweet corn production systems that can be manipulated to reduce crop loss from *H. zea* infestations. As previously described, male *H. zea* moths follow plumes of airborne sex pheromone produced by females. In small corn fields, mating can be reduced via disruption of pheromone communication between adult moths with synthetic pheromones (Mitchell and Mclaughlin 1982). The success of this strategy is contingent on *H. zea* moths mating after they have migrated and begin searching for a mate.

While a reduction in pest pressure might be possible at the field level using the air-permeation technique (i.e. mating disruption), a coordinated area-wide effort across the agricultural landscape has the highest likelihood of area-wide pest suppression (Cardé and Minks 1995). If more than one pest moth species is present, *H. zea* must be managed with all species using multiple chemical releases to carry out an effective pheromone disruption strategy (Mitchell et al. 1975, 1976, Cardé and Minks 1995).

Cultural Control. Pest avoidance is a widely researched strategy that utilizes knowledge of the plant-insect interactions between the host and the pest. Volatile emissions from fresh green silks are highly attractive to gravid *H. zea* females searching for locations to lay eggs (Flath et al. 1978, Cantelo and Jacobson 1979, Raina et al. 1992, Rhino et al. 2014). Past studies have shown that oviposition rates peak during fresh silk production, compared to later

reproductive and earlier vegetative stages of sweet corn development (Mitchell 1978, Latheef et al. 1991, Coop et al. 1992, Archer and Bynum 1994). Sweet corn plantings and/or harvest can be adjusted so that susceptible early silking corn is unavailable when females are searching for a host. This method significantly reduces the likelihood of ear damage by *H. zea* (Mitchell 1978, Coop et al. 1992). However, growers plant their sweet corn based on market demands that may preclude their ability to adjust planting times to avoid *H. zea* pressure.

Options to manage *H. zea* in sweet corn via the use of either a trap crop or push-pull strategy is limited because the success of a trap cropping or a push-pull strategy is contingent on including a host that would be more attractive than the cash crop (Shelton and Badenes-Perez 2006). Sweet corn is the most attractive host for *H. zea*, so this poses a great challenge. Perhaps, differences in sweet corn attraction could be created by manipulating the planting date or early maturing cultivars. For example, smaller plantings of non-cash crop sweet corn could be planted in proximity to the larger plantings of cash-crop sweet corn. Earlier plantings would produce silks earlier than those in the later plantings, thereby luring ovipositing *H. zea* away from the cash crop.

In contrast, sweet corn could be used to improve cultural management of *H. zea* in higher-value vegetable crops. For example, corn that is silking when *H. zea* is searching for an oviposition site could be used as a trap crop for this pest in tomato (Rhino et al. 2014). .

Host plant resistance. Plant varietal resistance to *H. zea* is another control option that may be economical and environmentally sensitive and is the cornerstone of IPM (Naranjo et al. 2008). Chemical analysis of silks of different corn varieties documented significant differences in cuticular lipids, maysin and isomaysin content, all of which significantly hinder larval development (Wiseman and McMillian 1982, Wiseman and Isenhour 1990, Wiseman et al. 1992,

Yang et al. 1992). Antifeeding compounds have a negative effect on *H. zea* fecundity by causing reductions in overall larval size and extended larval development time. Wiseman and Carpenter (1995) determined that growth inhibition factors in silk decrease protein absorption in *H. zea*, leading to malnutrition.

Biological control. Naturally occurring and augmentative biological control mechanisms have been examined for *H. zea* management in sweet corn production systems (Oatman 1966, Oatman and Platner 1970, Gross and Young 1984, Gross 1990, Reid 1991, Udayagiri et al. 1997, Pfannenstiel and Yeargan 2002, Musser and Shelton 2003, Musser et al. 2004). Natural enemies including *Coleomegilla maculata* (De Geer)*, Harmonia axyridis* (Pallas)*, Orius insidiosis* (Say)*,* and *Geocoris punctipata* (Say) are the most cited predators of *H. zea* eggs and early instars and have the highest probability of success in sweet corn (Oatman 1966, Reid 1991, Pfannenstiel and Yeargan 2002, Musser and Shelton 2003, Musser et al. 2004, Seagraves and Yeargan 2009). For example, *O. insidiosis* can destroy 12 to 74% of eggs in a 48-h period (Reid 1991) and when *C. maculata* is excluded from sweet corn ears, survival of *H. zea* eggs increases 20 to 40% (Seagraves and Yeargan 2009).

Other natural enemies have been evaluated to a lesser extent, and on a regional basis, because distributions are not uniform throughout the US. Species representing the families Tachinidae, Coccinellidae, and Chrysopidae are included in this second group (Oatman 1966, Oatman and Platner 1970, Gross and Young 1984, Gross 1990, Udayagiri et al. 1997).

Parasitic insects of *H. zea* in sweet corn are represented by many hymenopteran species as well as select dipteran species. In the US, hymenopteran parasitoids include *Trichogramma minutum* (Riley)*, Campoletis sonorensis* (Cameron)*, Hyposoter* spp., *Meloborus fuscifemora* (Graf)*, Chelonus texanus* (Cress) and *Apanteles militaris* (Walsh) (Oatman and Platner 1970,

Caron and Bradley 1978, Udayagiri et al. 1997). Dipteran parasitoids include *Archytas marmoratus* (Townsend) and *Lespesia* spp. (Caron and Bradley 1978, Udayagiri et al. 1997). Ichnuemonidae and Brachnonidae are also represented among parasitoids described in the literature (Oatman and Platner 1970).

Trichogramma pretiosum (Riley) and *Trichogramma chilonis* (Ishii) have been evaluated as potential biological control agents against *H. zea* eggs in sweet corn (Vargas and Nishida 1982, Neil and Specht 1990). *T. pretiosum H. zea* control varied from 7.4 to 53%. *T. chilonis* egg predation rate was 32%, on average but was as high as 92% under ideal weather conditions. In both cases, temperature, rainfall and pest density significantly influenced parasitism rates.

Viruses and bacteria have been evaluated for managing *H. zea* caterpillars (Hall and Dunn 1958, Ignoffo and Adams 1966, Hamm and Young 1971, Bell and Romine 1986, Bong and Sikorowski 1991, Bartels and Hutchison 1995, Feaster and Steinkraus 1996, Lua and Reid 2000, Granados et al. 2001). Viruses infecting *H. zea* include lepidopteran-specific baculoviruses, which are classified into alphabaculoviruses (nucleopolyhedroviruses) and betabaculoviruses (granuloviruses) (Jehle et al. 2006, Chiu et al. 2012). Prior to 2006, most research focused on the potential control of *H. zea* with "cytoplasmic polyhedral virus," which under current classification is most likely a nucleopolyhedrovirus (Ignoffo and Adams 1966, Bong and Sikorowski 1991, Lua and Reid 2000).

Laboratory and field tests have demonstrated variable rates of control using nucleopolyhedroviruses (NPHV) against *H. zea* when applied directly to larvae or to plant silks, (Ignoffo and Adams 1966, Hamm and Young 1971, Bell and Romine 1986, Bong and Sikorowski 1991, Lua and Reid 2000, Granados et al. 2001). For example, applications of nucleopolyhedrovirus (NPV), applied alone and with an insecticide to early-season sweet corn

resulted in significant yield improvements of 18.3 and 28.4%, respectively (Hamm and Young 1971). Granuloviruses have been evaluated in combination with *Bacillus thuringiensis* (Bt) for control of *H. zea* (Bell and Romine 1986, Granados et al. 2001). Unfortunately, the combination of these two pathogens were antagonistic, resulting in lower mortality rates than if either was used separately. One commercial NPV product, Gemstar®, is currently available in the United States and marketed by Certis (Columbia MD) for control of *H. zea.*

Bt-based insecticides are by far the most commonly evaluated bio-based products for *H. zea* control in sweet corn. Bt products were first examined for *H. zea* control in the 1950s (Hall and Dunn 1958). The use of Bt-based insecticides are still used in organic sweet corn production, sometimes in combination with Zea-later™II application methods and conventional systems growing traditional varieties (versus transgenic, discussed in the next section) (Hall and Dunn 1958, Bartels and Hutchison 1995). As of 2015, there are two formulated Bt products widely available for use against *H. zea*. Deliver® (Certis USA, Columbia MD) and DiPel® (Valent Biosciences, Libertyville, IL) both contain the 'kurstaki' Bt strain.

Chemical control. Synthetic insecticides became the most common control tactic for *H. zea* after World War II (Johnson 1944). Insecticide chemistries have evolved over time and products currently on the market for use in sweet corn against *H. zea* represent several different modes of action (IRAC 2014). Since 2000, insecticides used to control *H. zea* include members of the following classes (alphabetically): carbamates (IRAC group 1A), diamides (IRAC group 28), indoxacarbs (IRAC group 22A), pyrethroids (IRAC group 3A) and spinosads (IRAC group 5) (Musser and Shelton 2003, Hannig et al. 2009, IRAC 2014). Research shows that insecticidal compounds developed within the last 20 years have lower toxicity to nontarget beneficial insects. For example, indoxacarb and spinosad are less toxic to the most abundant naturally occurring

predators of *H. zea* in sweet corn, in contrast to pyrethroid insecticides (Musser and Shelton 2003).

Pyrethroid insecticides have been commonly used against *H. zea* in many major agricultural crops of the United States for >25 years. In certain regions, *H. zea* populations have developed resistance to pyrethroid insecticides. In 1997 and 1998, *H. zea* adult populations were surveyed throughout the US, and widespread but variable levels of pyrethroid resistance were observed. At two different doses delivered in a standardized manner to individual adult male moths, (5 ug and 10 ug, respectively), populations exhibited significant levels of pyrethroid resistance in Alabama (12% and 2%, respectively), Louisiana (18% and 22%, respectively), North Carolina (13% and 2%, respectively), South Carolina (17% and 6%, respectively), Tennessee (6% and 1%, respectively), and Texas (6% and 6%, respectively) (Martin et al. 1999).

Transgenics. Embryonic corn tissue was first transformed with genes from Bt var *kurstaki* in 1992 and progeny from that embryonic tissue significantly increased mortality of *O. nubilalis*. When the Bt-transformed line was crossed with a conventional field corn variety, the first stable hybrid corn varieties expressing a synthetic insecticidal protein were established (Armstrong et al. 1995). Sweet corn varieties expressing Bt insecticidal crystal (Cry) proteins for control of *H. zea* were first tested in 1997 (Lynch et al. 1999, Wiseman et al. 1999)..

Five Bt proteins expressed in field corn lines for control of *H. zea* are currently being marketed. Cry1F, Cry1Ab, Cry1A.105 and Cry2Ab2 produce Cry toxins in transformed corn plants. Vip3A, a vegetative insecticidal protein (Vip) derived from Bt, has also been transformed, but has a different mode of insecticidal action than Cry toxins. The first Bt sweet corn variety available in the United States was Syngenta's Attribute™, which expresses Cry1Ab, known as Bt event 11 (Hellmich et al. 2008, Shelton et al. 2008). This fresh-market, Bt-sweet

corn cultivar provided a 4-fold increase in control of *H. zea* compared with unsprayed non-Bt isoline (Speese et al. 2005). More importantly, this Bt cultivar provided an 86-fold increase in the percentage of marketable ears compared with the non-Bt isoline because the Bt cultivar also controlled *O. nubilalis*, *S. frugiperda* and by association reduced secondary infestations of pest invaders including sap beetles, *Carpophilus spp.* (Speese et al. 2005). As of 2015, Syngenta's Attribute™II and Syngenta's Performance series™ sweet corn products employ a "pyramid" (multiple Bt gene) approach. Cry1A.105 and Cry2Ab2 are pyramided in Syngenta's Performances Series™ product lines, which were released in 2013. Cry1Ab and Vip3A are pyramided in Rogers® and Syngenta's Attribute Series™ lines. Cry1F is currently expressed in field corn, but not sweet corn varieties.

Sweet corn varieties pyramided with Bt traits have been widely tested for efficacy. Cry1A.105/Cry2Ab2 sweet corn and Cry1Ab/Vip3A both reduce *H. zea* damage compared to non-Bt checks. Compared to each other, Cry1A.105/Cry2Ab2 sweet corn performed as well as, or significantly better than, varieties expressing Cry1Ab/Vip3A (Siegfried et al. 2000, Horner et al. 2003, Buntin 2008, 2010, Siebert et al. 2012, Bohnenblust et al. 2013, Edwards et al. 2013, Hoess et al. 2013, Shelton et al. 2013, Rule et al. 2014). Single-gene Bt sweet corn significantly reduces *H. zea* damage to ears compared to non-Bt varieties, but exhibits significantly more damage compared to pyramided Cry1A.105/Cry2Ab2 or Cry1A/Vip3A sweet corn varieties (Siebert et al. 2012, Rule et al. 2014). Pyramid-type sweet corn also provides broader control against common lepidopteran pest complexes and reduces the likelihood that *H. zea* will develop resistance to Bt toxins (Zhau et al. 2003, Bates et al. 2005).

Insect resistance management (IRM) in Bt field corn is well studied, but sweet corn represents only a small fraction of overall production when compared to field corn varieties in

the northeast United States (Bates et al. 2005, Burkness et al. 2011, Edwards et al. 2013, USDA 2014). For this reason, Bt sweet corn is exempt from United States Environmental Protection Agency regulations that would require Bt sweet corn to be planted with a proportion of non-Bt corn "refuge" to prevent the development of resistance by *H. zea* (Bates et al. 2005, Edwards et al. 2013). Bt sweet corn is compatible with biological control because proteins expressed in Bt sweet corn varieties have been shown to have no adverse affect on non-target beneficial organisms that are important for control of *H.* zea (Bartsch et al. 2008, Tian et al. 2012, 2013, Liu et al. 2014, Tian, Long, et al. 2014, Tian, Wang, et al. 2014).

In 2013, it was estimated that Bt sweet corn had captured <20% of the fresh market in the United States but no exact figures could be obtained (Shelton et al. 2013). However, based on its excellent performance in multiple trials it is clear that Bt sweet corn has the capacity to significantly reduce the use of conventional insecticides against lepidopteran pests and, in turn, reduce occupational and environmental risks that arise from intensive insecticide use. Whether this will be fully realized will depend on consumer acceptance.

Conclusions

A large body of research on *H. zea* management in sweet corn has accumulated since the early 20th century. This collection provides valuable insights about the biology, ecology and management of this important insect pest and should be used to refine our existing management programs. Moving forward, researchers and growers alike must adapt existing management strategies to consider climate change, new technologies, and new insights in agroecology.

There is widespread consensus among scientists that climate change is no longer a question of "if," but rather a matter of "when" (Oreskes 2004). The impacts of such changes on

H. zea biology are not currently known, but there are clues from other research evaluating lepidopteran species around the world (Parmesan et al. 1999, Hill et al. 2002, Both et al. 2009). The importance of understanding how these changes will alter the dynamics of *H. zea* development in sweet corn production in North America cannot be understated, because the agricultural landscapes in which the crop is currently grown have so much diversity. As stated earlier, overwintering potential is a function of soil temperature and the duration of exposure to extreme temperatures. Larval development rates increase as temperature increases. Climate change has the potential to affect long-term soil temperature profiles during overwintering periods, and may change regional weather patterns. In turn, this may affect *H. zea* by allowing it to overwinter in new areas and to produce multiple generations.

Modification and selection of plant traits is a tradition as old as human civilization and sweet corn is no different. Modern biotechnology and plant breeding techniques provide an opportunity moving forward to tailor sweet corn lines for enhanced resistance to *H. zea* infestation. Investment in enhancing traits such as husk length, silk density and silk maysin content, or inhibition of silk ethylene production may also hold promise as mechanisms for future control of *H. zea*. For vegetables, however, Bt sweet corn is the only new product of plant breeding and biotechnology that has demonstrated effective control of this important pest. Other insecticidal molecules derived from Bt or other organisms, or behavioral modifying traits, may become realities in the future.

Little is known about the defensive responses by sweet corn to herbivory, especially those induced by *H. zea*. Current ecological research shows that a complex system of chemical communication exists between plant host, herbivore, and natural enemies (Heil and Silva Bueno 2007, Howe and Jander 2008, Hermann and Thaler 2014). The chemical responses, or lack

thereof, within sweet corn to *H. zea* herbivory could generate new candidate mechanisms of control for use in conventional or transgenic control programs.

Chapter 2: Multivariate modeling improves prediction of *Helicoverpa zea* (Lepidoptera: Noctuidae) damage in sweet corn

Introduction

Corn earworm *Helicoverpa zea* (Lepidoptera:Noctuidae) is a polyphagous caterpillar pest found in the western hemisphere and is a key pest of sweet corn in the United States (Barber 1943, Phillips and Newson 1966, Cohen et al 1988, Coop et al 1992, Coop et al 1993, Shelton et al 2013, CABI 2014). Left unmanaged, *H. zea* caterpillars feed on corn ears, causing severe yield reductions and economic losses (Shelton et al 2013). Historically *Ostrinia nubilalis* (Hübner) (Lepidoptera: Crambidae) has been the major lepidopteran pest of sweet corn because of season-long pest pressure and its ability to infest all plant parts, but populations have declined significantly in recent years, along with associated damage. Because of this, more attention and resources are now being directed to managing *H. zea* (Hutchison et al 2010).

Female *H. zea* oviposit on sweet corn silks and yield loss occurs after caterpillars hatch, migrate to the ear and feed on corn kernels (Barber 1943, Hardwick 1965, Johnson et al 1975, Coop et al 1992). When a female moth finds a suitable plant host, she will deposit one or more eggs on the silks, then move to another plant, laying 800 to 1100 eggs in her lifetime (Barber 1943, Akkawi and Scott 1984, Coop 1993). After hatching, *H. zea* larvae move quickly toward the husk of the developing ear (Barber 1941). Inside the ear, they feed exclusively on corn kernels and do not exit the husk until pupation (Waldbauer et al 1984, Cohen et al 1988). *H. zea* have 5-6 instars with the last instar leaving the corn ear to pupate in the soil (Roach and Hopkins 1979).

Sweet corn is an important specialty crop grown throughout the United States for fresh market and processing purposes. Sweet corn is grown in 27 states that span diverse climatic regions across the United States, enabling year-round production and distribution to consumers in North America (Hansen et al 1999). In 2013, 96,591 ha of sweet corn were harvested for fresh market with a total value of $842.3M (US) and a per ha value of $8,720. In the same year, 127,510 ha were harvested for processing with a total value of $357.8M (US) and a per ha value of $2,806 (USDA NASS 2014).

Fresh market sweet corn has a low threshold for *H. zea* damage because a single larva or its damage can make the ear unmarketable. For fresh market purposes, the economic injury level (EIL) in a single plant is one larva, and the economic threshold per plant is also one insect. This paradox presents a challenge that requires a predictive management approach utilizing prophylactic treatments to prevent *H. zea* damage. For processing sweet corn, injury to the tip is normally removed and infestation of the ear tip by *H. zea* larvae is less of a concern.

Integrated pest management (IPM) practices for fresh-market sweet corn use counts of pheromone trap-captured male *H. zea* moths to inform treatment decisions (Boucher et al 2014, Shelton et al 2014). This approach is based on a linear relationship between male *H. zea* moths captured in pheromone or blacklight traps and free-flying females (Chowdhury et al 1987a, Chowdhury et al 1987b, Latheef et al 1993). Treatment decisions are based on male moth counts from pheromone traps taken at a regular interval during ear development. At each collection, a decision is made whether or not to spray, and how long the interval between sprays will be (Boucher et al 2014, Shelton et al 2014)

Significant economic damage may still occurr despite close adherence to these guidelines In this chapter, I argue that predictability of *H. zea* infestations in sweet corn can be

incrementally improved when additional biological and environmental factors are considered concomitantly with male *H. zea* trap catch numbers. Improvements using such an approach could increase yields and profit margins in high-value, fresh-market sweet corn.

IPM decision models that use pheromone trapping assume a linear relationship between adult male *H. zea* density and crop damage (Boucher et al 2014, Shelton et al 2014). However, other factors that influence reproductive success of *H. zea* in sweet corn can be used to add power to predictive damage models. These include (i) plant attractiveness, (ii) nocturnal flight behavior, (iii) daily temperature accumulation and (iv) precipitation.

Interactions between *H. zea* and sweet corn are driven by plant reproductive development stage. Sweet corn is a preferred host of *H. zea* and insects have higher rates of successful development on it than on secondary hosts (Akkawi and Scott 1984, Hayes 1988). Research also shows that *H. zea* infestations occur when eggs are laid on corn silk (Barber 1941, Coop et al 1993, Roach and Hopkins 1979). Females are attracted to ethylene produced by corn silks and, as a direct result, produce pheromones to attract a mate (Raina et al 1992).

Noctuid moths use the moon's azimuth as an orientation cue on clear nights (Sotthibandhu and Baker 1979). Furthermore, *H. zea* pheromone trap catch numbers are positively correlated with increasing moon illumination, and maximum catch values in Texas, USA have been shown to correlate with a full moon 71% of the time (Parajulee et al 1998). These factors may help *H. zea* moths to locate host silk volatiles and increase the probability of finding a suitable oviposition site (Ramaswamy 1988).

Precipitation can influence ovipositional behavior of noctuid moths directly or indirectly. High-altitude *Spodoptera exempta* (Walker) moth flights, measured by radar, decrease during moderate to heavy rainfall events, but a corresponding increase in ground-level moth densities

below 2 meters suggests that rain concentrates adult noctuid moth populations near ground level or plant height (Riley et al 1983). Plant response to rainfall could also have a positive indirect effect because plant ovipositional tissues may become more attractive. *Trichoplusia ni* (Hubner) (Lepidoptera: Noctuidae), the cabbage looper, responds preferentially to natural and artificial substrates with a higher moisture content when given a choice of ovipositional surfaces (Shorey 1964). *Heliothis virescens* (F.) oviposition also decreases as moisture content of ovipositional leaf substrates is reduced (Navasaro and Ramaswamy 1993).

Precipitation may also suppress parasitoid infestation rates and thus increase pest populations (Kumar et al 2009). *Trichogramma pretiosum* (Riley) and *Trichogramma chilonis* (Ishii) have been used as potential biological control agents against *H. zea* eggs in sweet corn systems (Vargas and Nishida 1982). In both species, there is an inverse negative relationship between rainfall and egg parasitism (Vargas and Nishida 1982, Yu et al 1984, Neil and Specht 1990, Kumar et al 2009).

H. zea developmental rate depends on the temperature of their surroundings (Vargas and Nishida 1982). Day-degree models have been developed to predict development of *H. zea* in sweet corn and economic loss that occurs as a result of infestations (Mangat and Apple 1966, Butler and Scott 1976, Wagner et al 1984). Temperature accumulation during development has a direct influence on successful *H. zea* development and subsequent damage to sweet corn ears at harvest.

The objectives of this study were to (i) evaluate the predictive power of male *H. zea* pheromone catches alone to predict sweet corn damage and (ii) determine whether the prediction was improved when trap catch was combined with information on crop stage, lunar illumination,

air temperature accumulation and precipitation. It was hypothesized that the predictive power of all factors combined would be higher than that of male pheromone trap catch alone.

Methods

Factor observations. Five factors were evaluated, alone and in combination, for their ability to predict damage to sweet corn ears at harvest. These factors included (i) reproductive silk stage of corn, (ii) *H. zea* population density (iii) lunar illumination, (iv) air temperature and (v) precipitation. Silk stage and subsequent dry-down was observed to estimate plant attractiveness to female *H. zea* moths durinig plant growth phases. Pheromone trap catches of male *H. zea* moths were used to estimate pest density. Proportional nightly illumination by the moon was calculated to account for *H. zea* behavior that uses moonlight to optimize ovipositional host seeking by females. Cumulative *H. zea* day-degrees were calculated using daily temperature data to predict larval development in sweet corn ears after hatch. Precipitation was measured because of its correlations with adult ovipositional patterns, suitability of plant substrates and parasitism.

Plant establishment and observations. Three plantings of sweet corn were established in 2011 and 2012 on farms at Cornell University's New York State Agricultural Experiment Station in Geneva, NY. In this study, farms are referenced as North (42.874590, -77.030100), South (42.864304, -77.028629), and Gates (42.869566, -77.053488). Seminis™ Obsession® non-Bt isoline variety sweet corn was planted on 76-cm centers with 23-cm within-row spacing. Each sweet corn field had dimensions of 30 m x 30 m and contained 5,100 plants.

Corn plants were randomly selected and marked with flagging tape shortly before the tassel stage in each of three fields during the 2011 and 2012 growing seasons (Wiatrak 2015).

When tassels became visible within the stalk, plant phenological development was observed at 3-d intervals until harvest was completed. A standardized visual quantification method was used (Figure 1) and observations were recorded as proportion of brown silk versus total silk volume using values of 0.00 (fresh silks, no dry down completely yellow), 0.05, 0.10. 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50, 0.55, 0.60, 0.65, 0.70, 0.75, 0.80, 0.85, 0.90, 0.95 or 1.00 (completely brown, dry), from first emerging green silk to harvest (Figure 1). Ears were manually harvested 21d after first silk and visually examined for larval presence.

Figure 1. Visual estimation gradient for calculation of silk dry down in sweet corn ears. Ears represent proportional dry silk values of (a) 0.00, (b) 0.25, (c) 0.75 and (d) 1.00.

***H. zea* population density**. *H. zea* population densities were estimated by collecting male moths from pheromone traps at 3-d intervals. Insects were collected using a series of three

Scentry™ Heliothis traps (Scentry Biologicals, Billings, MT) around each corn planting. Traps were placed at the midpoint on each of three sides of a field. Traps were baited with Hercon™ *Helicoverpa zea* lure tapes (Great Lakes IPM, Vestaburg, MI) and replaced at two-week intervals.

Nocturnal orientation. Moon phase data were obtained from the National Aeronautics Space Administration GSFC Eclipse web site (eclipse.gsfc.nasa.gov/eclipse.html) for 2011 and 2012. NASA provides lunar phase by calendar date in categorical form as new, first half, full, and last half moon. Lunar phase data were converted to proportional lunar illumination by converting each phase to a numerical percentage (proportional) values of 0, 50, 100, and 50% illumination values, respectively. Nightly cloud cover likely has an influence on lunar illumination, but could not be reliably quantified. For this reason, it was not considered in this study.

Temperature accumulation and rainfall. Daily minimum and maximum temperatures (°C), and rainfall (mm) were recorded at a weather station located at the Cornell University Agricultural Experiment Station in Geneva, NY (42.876607, -77.030800). *H. zea* developmental rate after oviposition was estimated using a base-12.5°C day-degree model (Mangat and Apple 1966).

Factor definitions. Four factor variables were calculated from datasets described above. These were total pheromone trap catch (TC), lunar illumination (I), total *H. zea* day-degrees and total precipitation. These factor values were calculated using methods described in sections that follow.

Plant phenological alignment. All measurements in this experiment were aligned to a plant-based phenological time scale instead of a calendar based time scale. Sweet corn

developmental rate is determined by environmental factors, not calendar date, and justified such an approach. Field data were aligned with sweet corn ear developmental phases of first green silk to 25% dry silk (GS-25%), 25% dry silk to 50% dry silk (25-50%), 50% dry silk to harvest (50%-H) and first green silk to harvest (GS-H). First green silk was recorded as the date on which first silk strands were observed emerging from the developing ear tip. Twenty-five percent and 50% dry silk were recorded as the dates on which silks reached respective stages of dryness, using methods described earlier. Harvest was recorded as the date on which an ear of corn was cut from the plant and evaluated for damage.

Day of year was used for alignment of silk stages with other model factors. First, plant silk observation dates were converted to day of year values on a 365-d scale. A 2^{nd} or 3^{rd} order polynomial function was then calculated for each observed plant (n=106) using phenological state (dry silk as a proportion of total silk mass) as the factor variable and day of year as the response variable (Table S1). Day of year values corresponding to first green silk, 25% dry silk, 50% dry silk and harvest for each plant were calculated from respective polynomial equations.

To align TC, I, T, and P factor variables with plant phenological time, factor observation dates were converted to day of year. Polynomial functions were calculated for TC, I, T and P (Table S2) and factor values were obtained using day of year values for GS, 25%, 50% and H of each observed plant. Factor variable totals were calculated within plant phenological phases by subtracting a factor value at phenological time A from phenological time B. For example, if TC at GS was n=10 and TC at 25% was n=50, TC for ΔGS-25% was n=40 (50 minus 10 equals 40). Total TC, I, T and P values were calculated for the phenological time periods of first green silk to 25% dry silk (ΔGS-25%), 25% dry silk to 50% dry silk (Δ25-50%), 50% dry silk to harvest (Δ50%-H) and (iv) first green silk to harvest (ΔGS-H) for each observed plant (Table S3).

Comparative predictive analysis. Nominal logistic regression was used to generate R^2 values for comparative predictive purposes (JMP 11.0, SAS Institute, Cary, SC). This approach allowed us to identify models that produced the highest correlation coefficients. In all cases, the nominal variable of ear damage state (damaged or clean) at harvest evaluation was designated as the response variable. Each model was aligned with plant silking periods of ΔGS-25%, Δ25-50%, Δ50%-H and ΔGS-H. Within each plant silking period, a full factorial nominal logistic model was calculated using factor combinations of (i) TC, (ii) I, (iii) T, (iv) P, (v) TC+I, (vi) TC+T, (vii) TC+P, (viii) TC+I+T, (ix) TC+I+P, (x) TC+T+P, (xi) TC+I+T+P, (xii) I+T, (xiii) I+P, (xiv) T+P, and (xv) I+T+P.

Predictive power optimization. Factors identified from nominal logistic models as having the highest correlation coefficients within each of the plant phenological phase categories were used as covariates in a predictive (versus descriptive) discriminant analysis (PDA) where damage state (clean vs damaged) was specified as the categorical variable (Huberty and Hussein 2003). A second series of PDA were completed using TC as the only covariate compared to silking period categories. Misclassification rates, defined as the proportion of observations incorrectly categorized by the PDA model compared to the actual dataset observations, of the TC model and revised TC+I+T+P model within each silking period were evaluated to determine differences in predictive model power.

Results

Trap catch predictive power. Datasets from 2011, 2012 and both years combined consistently showed that TC predictive power, by itself , is a weak predictor of sweet corn damage at harvest when compared to other models evaluated (Table 1, Table 2, Table 3). In

2011 TC R^2 was never greater that 0.002 (Table 1). In 2012, an R^2 of 0.016 was measured during the 25% to 50% dry silk period, but was nonetheless a weak predictive factor within that timing period compared to other models tested (Table 2). When 2011 and 2012 datasets were combined, TC resulted in R^2 ranging from 0.095 to 0.263 (Table 3). Compared to other factor models, however, TC alone still was not the best predictor of sweet corn damage at harvest.

Table 1. 2011 nominal logistic regression model correlation coefficients (R^2) calculated using full-factorial analysis to measure predictability of selected model variables. Measurements of trap catch (TC), lunar illumination (I), *Helicoverpa zea* day-degree accumulation (T) and precipitation (P) were used as model parameters. Within each column, the coefficient that best explains variability among all column models is highlighted.

				Corn silk period[1]			
TC	I	T	P	GS to 25%	25 to 50%	50% to H	GS to H
✓	-	-	-	*0.002*	*0.002*	*0. 002*	*0. 001*
✓	✓	✓	✓	**0.036**	**0.033**	**0. 101**	**0. 062**
✓	✓	✓	-	0.014	0.004	0. 018	0. 007
✓	✓	-	-	0.007	0.002	0. 018	0. 007
✓	✓	-	✓	0.027	0.010	0. 019	0. 013
✓	-	✓	✓	0.031	0.021	0. 003	0. 017
✓	-	✓	-	0.014	0.003	0. 003	0. 003
✓	-	-	✓	0.027	0.009	0. 003	0. 008

-	✓	✓	✓	0.034	0.031	0. 050	0. 059
-	✓	✓	-	0.014	0.003	0. 015	0. 007
-	✓	-	✓	0.027	0.009	0. 013	0. 013
-	✓	-	-	0.004	0.000	0. 012	0. 006
-	-	✓	✓	0.027	0.021	0. 002	0. 017
-	-	✓	-	0.012	0.002	0. 002	0. 003
-	-	-	✓	0.026	0.009	0. 002	0. 008

[1] 1st observed green silk (GS); 25% or 50% dry corn silk on a ear and harvest (H).

Table 2. 2012 nominal logistic regression model correlation coefficients (R^2) calculated using full-factorial analysis to measure predictability of selected model variables. Measurements of trap catch (TC), lunar illumination (I), *Helicoverpa zea* day-degree accumulation (T) and precipitation (P) were used as model parameters. Within each column, the coefficient that best explains variability among all column models is highlighted

				Corn silk period[1]			
TC	I	T	P	GS to 25%	25 to 50%	50% to H	GS to H
✓	-	-	-	*0.010*	*0.016*	*0. 004*	*0. 015*
✓	✓	✓	✓	**0.271**	**0.293**	**0. 324**	**0. 278**
✓	✓	✓	-	0.102	0.248	0. 014	0. 255
✓	✓	-	-	0.088	0.227	0. 008	0. 196

✓	✓	-	✓	0.099	0.248	0. 136	0. 265
✓	-	✓	✓	0.097	0.140	0. 147	0. 144
✓	-	✓	-	0.048	0.023	0. 008	0. 023
✓	-	-	✓	0.095	0.139	0. 116	0. 141
-	✓	✓	✓	0.267	0.278	0. 225	0. 236
-	✓	✓	-	0.101	0.157	0. 009	0. 198
-	✓	-	✓	0.099	0.247	0. 132	0. 220
-	✓	-	-	0.086	0.150	0. 002	0. 192
-	-	✓	✓	0.096	0.093	0. 091	0. 093
-	-	✓	-	0.046	0.022	0. 007	0. 022
-	-	-	✓	0.091	0.089	0. 087	0. 089

[1] 1st observed green silk (GS); 25% or 50% dry corn silk on a ear and harvest (H).

Table 3. Nominal logistic regression model correlation coefficients (R^2) calculated using full-factorial analysis of a combined 2011/2012 dataset to measure predictability of selected model variables. Measurements of trap catch (TC), lunar illumination (I), *Helicoverpa zea* day-degree accumulation (T) and precipitation (P) were used as model parameters. Within each column, the coefficient that best explains variability among all column models is highlighted.

				Corn silk period[1]			
TC	I	T	P	GS to 25%	25 to 50%	50% to H	GS to H
✓	-	-	-	*0.095*	*0.263*	*0.103*	*0.260*

✓	✓	✓	✓	**0.446**	**0.472**	**0.425**	**0.480**
✓	✓	✓	-	0.274	0.324	0.303	0.308
✓	✓	-	-	0.182	0.301	0.161	0.287
✓	✓	-	✓	0.348	0.363	0.321	0.375
✓	-	✓	✓	0.368	0.370	0.362	0.371
✓	-	✓	-	0.247	0.269	0.242	0.266
✓	-	-	✓	0.344	0.337	0.272	0.338
-	✓	✓	✓	0.361	0.387	0.404	0.418
-	✓	✓	-	0.076	0.069	0.138	0.070
-	✓	-	✓	0.334	0.324	0.275	0.324
-	✓	-	-	0.052	0.000	0.000	0.015
-	-	✓	✓	0.338	0.342	0.334	0.341
-	-	✓	-	0.008	0.054	0.121	0.047
-	-	-	✓	0.334	0.320	0.215	0.321

[1] 1st observed green silk (GS); 25% or 50% dry corn silk on a ear and harvest (H).

Comparative model screening. Models that used TC+I+T+P outperformed all other models in 2011 and 2012, as well as in combined models derived from pooled 2011 and 2012 datasets (Table 1, Table 2, Table 3)). Furthermore, TC+I+T+P models derived from the combined 2011 and 2012 dataset had the highest comparative R^2 values within any given period of silk development compared to either 2011 or 2012 alone. Among ΔGS-25% models derived

from the combined 2011/2012 dataset, TC+I+T+P had the highest correlation coefficient (0.446) and explained 4.7 times the variation in damage status compared to TC alone (0.095). Among Δ25-50% models, TC+I+T+P had the highest correlation coefficient (0.472) and explained 1.8 times the variation in damage status compared to TC alone (0.263). Among Δ50%-H models, TC+I+T+P had the highest correlation coefficient (0.425) and explained 4.1 times the variation in damage status compared to TC alone (0.103). Among ΔGS-H models, TC+I+T+P had the highest correlation coefficient (0.480) and explained 1.8 times the variation in damage status compared to TC alone (0.260).

Model accuracy. During the ΔGS-25% silking period using the combined 2011/2012 dataset, misclassification using a TC+I+T+P PDA model (17.9%) was 12.3% lower than the TC model (30.2%) (Table 2). During Δ25-50% phase, TC+I+T+P misclassification (17.9%) was 1.9% lower than TC (19.8%). During the Δ50%-H phase, TC+I+T+P misclassification (17.9%) was 7.6% lower than TC (25.5%). During the ΔGS-H phase, TC+I+T+P PDA misclassification (17.9%) was 1.9% lower than TC (19.8%).

Table 4. Results of predictive discriminant analysis (PDA) using a pooled 2011/2012 dataset of accumulated trap catch (TC) alone or TC combined with lunar illumination (I), *Helicoverpa zea* day-degree accumulation (T) and accumulated precipitation (P) during respective sweet corn silking periods to predict clean or damaged sweet corn ears at harvest.

		Misclassified				
		TC		TC+I+T+P		
Corn silk period	plants	n	%	n	%	difference (%)
Green silk to 25% dry	**107**	**32**	**30.2**	**19**	**17.9**	**12.3**

25% dry to 50% dry	107	21	19.8	19	17.9	1.9
50% dry to harvest	107	27	25.5	19	17.9	7.6
Green silk to harvest	107	21	19.8	19	17.9	1.9

Discussion

The hypothesis tested here was that predictive power of all factors combined would be greater than that of male pheromone trap catch alone. These results show that prediction of ear damage using trap catch alone as a predictor resulted in lower correlation coefficients, compared to TC+I+T+P models regardless of silking period across years. A full combined-factor model consistently produced higher R^2 values across years (Table 1, Table 2). In addition, a model built using a combined 2011/2012 dataset yielded the highest overall correlation coefficients of any other model tested in a single year alone. Taken together, these results support our stated hypothesis.

To date, the importance of interactions between *H. zea* female moths and sweet corn host plants has not been considered in the context of IPM strategies for pest control. Historically, male population abundance, measured using pheromone traps, has been the only basis for various control tactics (Boucher et al 2014, Shelton et al 2014). Our results demonstrate, however, that male *H. zea* trap catch explains at best only 26.3% of the observed variation in ear damage during any given plant phenological stage.

Precipitation was the only predictor to produce R^2 values greater than 0.25. Within ΔGS-H silking periods using the combined 2011/2012 dataset, for example, total rainfall was significantly lower among clean (33.7±15.7) versus damaged (59.8±2.5) ears (F=66.18,

df=1,p<0.0001) (Figure 2). This is largely an effect of year, but precipitation correlation coefficients > 0.30 in three out of four plant phenological phases are worth noting. Without precipitation included as a factor, most models lost considerable predictive power. This was interesting, and I hypothesize that the biological relevance of rainfall is based on its influence of *H. zea* flight patterns, suitability of plant ovipositional sites, parasitism rates, or some combination of these factors, as reported in the literature (Shorey 1964, Vargas and Nishida 1982, Riley et al 1983, Ramaswamy 1988, Kumar et al 2009). More research is needed to test this hypothesis because it could be an important next step toward further improvement of IPM predictive damage models beyond work described in this paper.

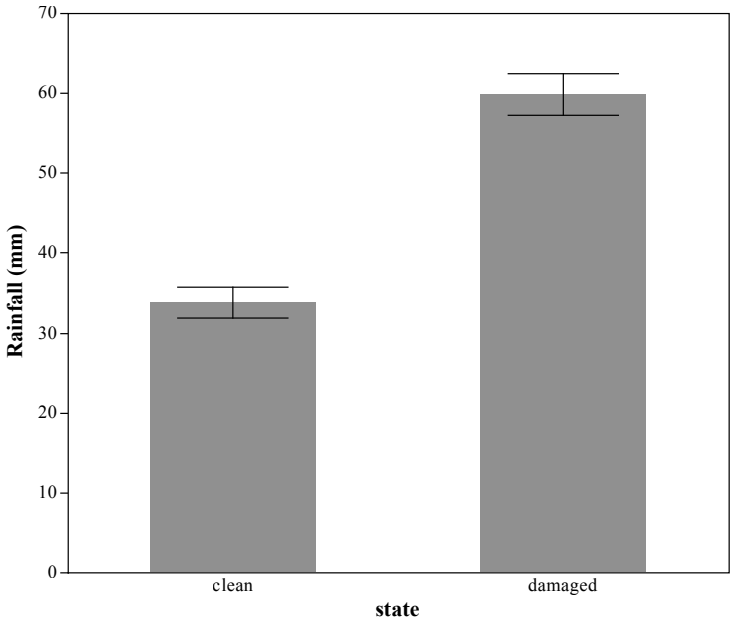

Figure 2. Total rainfall (mm) from first green silk to harvest among clean (33.7±15.7) and damaged (59.8±2.5) plants (F=66.18, df=1,p<0.0001)

Results show that any single factor was not a good predictor of ear damage during any silking period (Table 1). On the contrary, as more factors were considered, explanatory power of models incrementally improved. A full factorial model including all variables had the highest correlation coefficient in every phenological phase evaluated.

The literature suggests that a better understanding of insect-host interactions might also advance current IPM practices and, in turn, improve sweet corn crop yield. Female *H. zea* moths have a high affinity for ethylene volatiles produced by corn silks (Raina et al 1992). Once detected, ethylene volatiles activate a biochemical pathway in the female resulting sex pheromone production (Raina et al 1992). When a female is ready to lay eggs, she preferentially searches for sweet corn silk on which to deposit eggs, even when other suitable plant hosts are available (Barber 1941, Roach and Hopkins 1979, Coop et al 1993, Sudbrink and Grant 1995, Kennedy and Storer 2000).

Despite these facts, there isn't a clear understanding of volatile production over time after pollination occurs and silks begin to dry. Questions remain, including whether ethylene production diminishes as silks dries, whether female moths find dry silks suitable for oviposition and whether neonate *H. zea* larvae survive on dry silk until reaching the ear. While our results can be used to advance current IPM practices for *H. zea* in sweet corn, more research is needed to improve our general understanding of plant-insect interactions during the sweet corn ear development period.

The probability of damage in sweet corn by *H. zea* is the outcome of multiple factors and their interactions. Pheromone trapping has, and continues to be, a useful tool for IPM-based strategies for *H. zea* control in sweet corn. But, effective IPM practices can only be

implemented with reliable information on which to base management decisions. Trap catch by itself seems to explain only a small proportion of the total variability in sweet corn damage.

This study demonstrate\s the viability of predictive modeling that considers interactions of multiple environmental and biological factors. Approaches like this, combined with advances in web-based interactive technology such as smart phone apps and real-time weather data streams, can create new opportunities for IPM implementation. Programs such as the New York State Integrated Pest Management Program Sweet Corn Pheromone Trap Network (https://sweetcorn.nysipm.cornell.edu/, Cornell University) and PestWatch (http://www.pestwatch.psu.edu/sweet_corn.htm, Penn State University) have already started doing this. Statistical models that predict damage outcome in agricultural systems like sweet corn can be hosted and maintained on servers, while the user who interfaces with a website or smart device, only needs to provide a real-time observations. Factors such as rainfall and lunar illumination can be automated for model inclusion, leaving only trap count and crop stage to be supplied by the grower.

H. zea presents a significant management challenge to sweet corn production throughout the United States. Tools and datasets are available to researchers that now allow a closer look at the way in which insect herbivores and crop hosts interact with each other and respond to environmental variables. In the future, these observations will reveal important insights that can then be translated and used to advance IPM strategies.

Chapter 3: Effects of insecticide and application timings on corn earworm (Lepidoptera: Noctuidae) management in sweet corn

Helicoverpa zea (Boddie), the corn earworm, is a key pest of sweet corn in many parts of the United States (Barber 1943, Phillips and Whitcomb 1962, Coop et al. 1992, 1993, Shelton et al. 2013). *H. zea* is restricted to the western hemisphere (Cohen et al. 1988, CABI 2014) and its damage to sweet corn in the United States has increased while another key caterpillar pest, *Ostrinia nubilalis* (Hübner), the European corn borer has decreased in importance in the Midwest corn belt since the 1990s (Hutchison et al. 2010). Left unmanaged, *H. zea* can cause severe yield reduction and economic losses (Horner et al. 2003, Hutchison and Storer 2010, Shelton et al. 2013).

H. zea infestation, and subsequent yield loss, occurs when larvae enter the tip of sweet corn ears and feed (Hardwick 1965, Coop et al. 1992). This process begins when adult females are attracted to plant volatiles emitted by fresh corn silks (Flath et al. 1978, Cantelo and Jacobson 1979, Raina et al. 1992). After a suitable plant host is located, one or more eggs are deposited directly on fresh silk (Barber 1943). A single female can lay from 800 to 1100 eggs in her lifetime (Akkawi and Scott 1984).

Sweet corn is a preferred host of *H. zea* which has a higher rate of survival on this host compared with other hosts (Johnson et al. 1975, Hayes 1988). The presence of a single *H. zea* larva renders a sweet corn ear unmarketable for the higher value fresh-market sale. Typically, *H. zea* only infests the tip of the sweet corn ear, and the ear tip can be mechanically removed allowing what is left of the cob to be used for processing (Shelton 1986).

Current integrated pest management (IPM) practices for fresh-market and processing sweet corn in the northeast United States use pheromone traps to monitor male *H. zea* moth activity near sweet corn fields from which treatment decisions are made (Boucher et al. 2014, Shelton et al. 2014). Treatment decisions are based on the number of moths captured over a pre-determined period of time during ear development starting when the ear (female flower) produces silk (the stigma and style) to be pollinated (Clemson University Cooperative Extension 2015). Treatments continue until harvest based on the number of moths trapped per unit of time . This approach relies on research showing that male moths captured in pheromone traps adequately represent female moth populations in the same area (Chowdhury et al. 1987a, 1987b). Typically, growers use multiple applications of pyrethroid insecticides to successfully manage *H. zea* infestations in sweet corn (Shelton et al. 2013). However, there is concern about pyrethroid resistance as well as interest for more efficacious, safer and longer residual products to reduce damage loads (Jacobson et al. 2009).

A new insecticide class, the anthranilic diamides, include products that are longer-lasting and have a narrow-spectrum of activity, especially against Lepidoptera (Lai and Su 2007, Hannig et al. 2009). Examination of this chemical class against *H. zea* has not been extensively tested under field conditions. Chlorantraniliprole may control *H. zea* in sweet corn with fewer applications, but research is needed to explore such a question.

The first objective of this project was to evaluate *H. zea* control by initiating an insecticide spray program earlier than traditionally recommended by targeting the late tasseling/very early silk stage of sweet corn rather than waiting until mid-green silk. We hypothesized that targeting late tassel/first green silk with an insecticide would improve *H. zea* control compared to the traditional application timing that begin at the mid-green silk stage. The

second objective was to compare *H. zea* control using different insecticides. We hypothesized that chlorantraniliprole would provide superior *H. zea* control compared to products containing lambda-cyhalothrin and methomyl. Finally, we hypothesized that the best *H. zea* control would be obtained by targeting late tassel/first green silk stage with chlorantraniliprole.

Methods

Plot establishment. Experimental plots were established on 14 June 2012 and 8 July 2014, respectively, at the Cornell University's Agricultural Experiment Station Fruit and Vegetable Research Farm located in Geneva, NY (42.872692, -77.019242). Plots were also established in 2013, but *H. zea* moths were not detected and no damage was recorded. 'Obsession' and 'EX08767143' conventional fresh-market sweet corn varieties were planted in 2012 and 2014, respectively (Seminis™ Vegetable Seeds, St. Louis MO). Fields were seeded on 76-cm centers and 20-cm in-row plant spacing using a Monosem™ vacuum seeder (Edwardsville, KS). Nitrogen was added at a rate of 57 kg per ha in the furrow with seed at planting time. An additional 57 kg of N per ha was side-dressed when plants reached the seven-leaf stage.

Insecticide treatments. Methomyl (Lannate® LV, DuPont™, Wilmington, DE), chlorantraniliprole (Coragen® SC, DuPont™, Wilmington, DE) and lambda-cyhalothrin (Warrior®, Syngenta™, Greensboro, NC [2012] and Lambda-T®, Helena Chemical™, Collierville, TN [2014]) were selected as insecticide treatments. All three were applied using maximum labeled rates of 504.3 g AI methomyl, 73.2 g AI chlorantraniliprole and 33.6 g AI lambda-cyhalothrin per hectare.

Insecticide treatments were made using a 5-row CO_2 pressurized Hagie 200 High-Boy tractor (Hagie Equipment Company, Clarion, IA) equipped with 3 Tee-Jet flat fan 11003 nozzle tips per row (one over the top and one drop nozzle on each side aimed at the ear zone), delivering 137 L H_2O per ha at 2.8 kg per cm^2 pressure and a speed of 5.1 kph. The adjuvant 'Dyne-Amic' (Helena Chemical™, Collierville, TN), a modified vegetable oil and organosilicone surfactant blend, was added to all treatments at a 0.1% v/v ratio.

Insecticide timing. Insecticides were applied using one of 5 prescribed timing treatments based on plant developmental phase or current IPM practices (Boucher et al. 2014, Shelton et al. 2014). Prescribed timing treatments encompassed tassel and silking stages (Clemson University Cooperative Extension 2015). Timing treatments were (1) three sprays from first green silk to 25% dry silk, (2) 1 spray at first green silk, (3) sprays as needed per IPM recommendations from 50% silk to harvest based on pheromone catches, (4) 1 spray at 50% tassel, (5) 4 sprays from 50% tassel to 25% dry silk and (6) an untreated check (Table 3). In 2014, all timing intervals were evaluated, but in 2012 only timing intervals 1, 2 and 3 were evaluated.

Table 5. Number of insecticide applications made in 2012 and 2014 for designated timing treatments.

Year	Treatment	Applications
2012	1	1
	2	3
	3	6

2014	1	1
	2	3
	3	4
	4	1
	5	4

Only primary ears, those that develop first and highest on the plant, were evaluated. First green silk was defined as the date of first observed silk, of any length, emerging from any of 25 randomly sampled ear tips. Fifty percent green silk was defined as the day on which >50% of 25 randomly sample ears reached silk stage. Fifty percent tassel was defined as the date on which >50% of 25 randomly sampled plants displayed a tassel.

Pest pressure. The prescribed timing treatment (3), described above, required an estimate of adult pest pressure based on pheromone trap catch values. Three Scentry® Heliothis traps (Great Lakes IPM Inc., Vestaburg, MI) were placed around the perimeter of each field in 2012 and 2014. Traps were checked for adult male moths at 3-day intervals when corn plants reached the final vegetative stages of development. Applications to treatment (3) plots were made according to current guidelines (Boucher et al. 2014, Shelton et al. 2014) using pheromone trap counts to determine application frequency (Table 4).

Table 6. Summary of male *Helicoverpa zea* (Lepidoptera: Noctuidae) pheromone trap catches and respective insecticide application dates for

treatment (3), 50% silk to harvest, in 2012 and 2014 during the period of reproductive sweet corn ear development.

Year	App No.	Date	Mean trap catch/day	Corresponding spray interval
2012	tassel	12 Aug	0.0	-
	1	15 Aug	7.0	4 d
	2	19 Aug	28.3	3 d
	3	22 Aug	30.0	3 d
	4	25 Aug	22.3	3 d
	5	28 Aug	18.0	3 d
	6	31 Aug	13.7	3 d
	harvest	2 Sep	-	-
2014	tassel	2 Sep	0.0	-
	1	5 Sep	1.3	4 d
	2	9 Sep	3.0	4 d
	3	13 Sep	1.4	4 d
	4	17 Sep	0	-
	harvest	22 Sep	-	-

Experimental design. Treatment plots consisted of 3 rows, 8 m in length. A randomized complete block design was implemented in 2012 and 2014, with each treatment replicated 4

times annually. In 2012, methomyl, chlorantraniliprole and lambda-cyhalothrin were evaluated in combination with timing treatments (1), (2) and (3). In 2014, chlorantraniliprole and lambda-cyhalothrin were evaluated combined with timing treatments (1), (2), (3), (4) and (5).

Field evaluation. Treatments were evaluated 21 d after first green silk in each year. Twenty-five randomly selected primary ears of corn were harvested from the center three rows of treatment plots. Ears without damage or larvae in the silk or on the kernels inside the husk were classified as clean. Ears with larvae in the silk or on the ear were classified as damaged.

Statistical analysis. JMP 11.0 for Macintosh (SAS Institute, Cary SC) was used for statistical analysis. Pest pressure was much higher in 2012 compared to 2014. In 2014, additional timing intervals (1 and 2) were added, chlorantraniliprole was added as an insecticide treatment to evaluate diamide action when applied at different times, and methomyl was excluded. For these reasons, 2012 and 2014 datasets were not combined. Instead, each year was evaluated separately using linear mixed model regression. Insecticide and timing interval were assigned as main effects, insecticide*timing interactions effects were measured, and replicate was assigned as a random effect. Tukey HSD (p=0.05) were used to separate treatment means, when appropriate. The untreated control was not included in the analyses, but results are presented.

Results

In 2012, the main effects of insecticide (F=1.8521, df=2, p=0.1763) and timing (F=1.8723, df=2, p=0.1732) were not significant. In contrast, the interaction effect between insecticide and timing was significant (F=6.1220, df=4, p=0.0012) (Table 7). While control of *H. zea* was similar using all lambda-cyhalothrin application timings and *H. zea* control was

similar using all chlorantraniliprole applications timings, *H. zea* control in the methomyl treatment timed following treatment (1) was significantly greater than control in the methomyl treatment timed following treatment (3).

Table 7. Interaction effects of insecticide and application timing against larval infestations of corn earworm in sweet corn ears in 2012.

Effect	Insecticide	Timing[1]	n	mean (+/- SE)[2]	
Insecticide*timing	Lambda-cyhalothrin	1	4	60.5 ± 2.5	ab
		2	4	62.2 ± 3.6	ab
		3	4	65.5 ± 1.6	ab
	Chlorantraniliprole	1	4	68.0 ± 5.8	ab
		2	4	67.3 ± 1.0	ab
		3	4	75.8 ± 3.7	a
	Methomyl	1	4	80.7 ± 4.3	a
		2	4	68.5 ± 11.1	ab
		3	4	45.5 ± 3.1	b
	Untreated check	6	4	37.0 ± 11.8	-

[1] (1) 1st green silk to 25% dry silk (3 sprays), (2) 1st green silk (1 spray), (3) 50% green silk to harvest (as needed)*, (4) 50% tassel (1 spray) and (5) 50% tassel to 25% dry silk (1 spray).

[2] Means followed by different letters are signficicantly different (Tukey HSD, p=0.05).

In 2014, the main effects of insecticide (F=7.8148, df=1, p=0.0090) and timing (F=4.7464, df=4, p=0.0044) were significant, but the interaction between insecticide and timing was not significant (F=0.6458, df=4, p=0.6342) (Table 8, Table 9). In 2014, lambda-cyhalothrin treatments (57.8 ± 3.4) had signficantly lower percentage of clean sweet corn ears compared to chlorantraniliprole treatments (69.8 ± 3.7). Among 2014 timing treatments, insecticides applied 4 times from 50% tassel to 25% dry silk (76.5 ± 3.2) had significantly higher percentages of clean ears than insecticides applied once at 50% harvest (47.5 ± 5.5) Other treatments were not signficantly different from each other.

Table 8. Insecticide as a main effect against larval infestations of corn earworm in sweet corn ears in 2014.

Effect	Insecticide	n	% clean (+/- SE)[1]
Insecticide	Lambda-cyhalothrin	20	57.8 ± 3.4 b
	Chlorantraniliprole	20	69.8 ± 3.7 a

[1] Means followed by different letters have significantly different interaction effects (Tukey HSD, p=0.05).

Table 9. Application timing as a main effect against larval infestations of corn earworm in sweet corn ears in 2014.

Effect	Timing[1]	n	% clean (+/- SE)[2]
Timing	1	8	64.0 ± 6.1 ab
	2	8	67.0 ± 3.6 ab
	3	8	64.0 ± 6.5 ab
	4	8	47.5 ± 5.5 b
	5	8	76.5 ± 3.2 a

[1] (1) 1st green silk to 25% dry silk (3 sprays), (2) 1st green silk (1 spray), (3) 50% green silk to harvest (as needed)*, (4) 50% tassel (1 spray) and (5) 50% tassel to 25% dry silk (1 spray)

[2] Means followed by different letters are signficicantly different (Tukey HSD, p=0.05).

Discussion

Chlorantraniliprole is cited as an efficacious chemistry having plant systemic activity and long-lasting protection against arthropod pests (Hannig 2009). Results from 2012, however, show superior control to other treatments in only one case when applied from first green silk to 25% dry silk versus methomyl applied during the same timing interval (Table 7). Nine different insecticide timing treatments were evaluated in 2012, yet chlorantraniliprole achieved superior control in only one instance and there was no evidence of superior control when compared to other chemistries. In 2014, insecticide was significant as a main effect and chlorantraniliprole resulted in significantly higher numbers of clean sweet corn ears compared to lambda-cyhalothrin treatments (Table 8). 2014, however also had less pest pressure compared to 2012 (Table 9).

The effects of insecticide timing treatment were not consistent. In 2012, application timing made no difference when lambda-cyhalothrin was used, nor was it significant for chlorantraniliprole (Table 7). Methomyl control of *H. zea* significantly improved, however, when applied from first green silk to 25% dry silk, versus timing treatments 1 and 2. In 2014, the main effect of timing significantly improved the percentage of clean corn ears when insecticides were applied from 50% tassel to 25% dry silk (Table 9). Insecticide applications made using current IPM guidelines were not significantly different from applications made once at 50% tassel or first green silk, or three applications made from first green silk to 25% dry silk.

These results suggest that targeting late tassel/first green silk with an insecticide could improve *H. zea* control compared to the traditional application timing beginning at the mid-green silk stage, thus supporting our first hypothesis. Significant improvements were seen when methomyl was applied during the window of first green silk to 25% dry silk versus other timing treatments. In 2014, significant improvement in percentage of clean ears was observed among treatments applied from 50% tassel to 25% dry silk versus other timing treatments.

In 2012, however, we were unable to show that chlorantraniliprole provided superior *H. zea* control compared to products containing lambda-cyhalothrin and methomyl, but were able to do so in 2014. Based on these findings, the suitability of chlorantraniliprole as an effective means of *H. zea* control in sweet corn is unclear.

2014 results show that chlorantraniliprole provided significantly better control of *H. zea* than lambda-cyhalothrin and that insecticide treatments applied from 50% tassel to 25% dry silk produced significantly higher yields than a single spray applied at 50% tassel. No significant differences were found between timing other timing treatments. These results support the hypothesis that the best *H. zea* control can be obtained by targeting late tassel/first green silk

stage with chlorantraniliprole, but with a caveat that this conclusion is only valid based on 2014 results.

Pyrethroid insecticides are the most commonly used insecticide in sweet corn production. But, significant yield improvements using lambda-cyhalothrin with standard IPM guidelines (treatment 3), or even modified timing treatments to target very early silk stages (treatment 1) were not significant. The reasons for this are unclear. Pyrethroid resistance has been reported in *H. zea* populations from the southern United States (Pietrantonio et al. 2007, Hopkins and Pietrantonio 2009, 2010), and in the midwest (Jacobson et al. 2009). There is no published evidence of this in New York. However, it is possible that resistance contributed to control failures of lambda-cyhalothrin in our experiments. Laboratory screening assays of NY field-collected adults in 2010 and 2011 have been conducted and suggest that a low level of resistance was present (Olmstead and Shelton unpublished).

Chlorantraniliprole represents a relatively new class of insecticide. Anthranilic diamides have a very specific mode of action (Cordova et al. 2006), have fewer non-target effects in the field (Preetha et al. 2009, Brugger et al. 2010, Gradish et al. 2011, Huang et al. 2011) and reported to have long-lasting plant systemic activity due to their ability to act systemically in plants and have anti-feeding effects on target pest insects (Hannig et al. 2009). But, results of this study suggest that the suitability of chlorantraniliprole for use in sweet corn to control *H. zea* infestation is unclear across years. If, however, 2014 results are considered alone, chlorantraniliprole is more efficacious compared to lambda-cyhalothrin (Table 6).

In 2014, timing treatment 5 used 4 insecticide sprays applied from first green silk to 25% dry silk. A comparison of environmental impact quotient values (EIQ) (Kovach et al. 1992) demonstrates similar ecological benefits of using chlorantraniliprole or lambda cyhalothrin. At

rates used in our study, chlorantraniliprole and, lambda-cyhalothrin and chlorantraniliprole had per application ecological EIQ values of 3.1 and 2.4, respectively (NYSIPM program, www.nysipm.cornell.edu/EIQCalc/input.php). Total ecological EIQ for all applications (n=3) based on current IPM guidelines were 12.4 for lambda-cyhalothrin and 9.6 for chlorantraniprole.

This research demonstrates that *H. zea* management in sweet corn is influenced by insecticide chemistry and application timing. The results also show that successful outcomes varied between years. In 2012, only the interaction effects between insecticide and timing were significant, whereas in 2014 only main effects of insecticide and timing were significant. Chlorantraniliprole provided inconsistent results in 2012, but had significantly higher percentanges of clean sweet corn ears among treatments compared to lambda-cyhalothrin.

Epilogue: Management of *Helicoverpa zea* (Boddie) in the 21st century

Contemporary monitoring practices used to making control decisions for *Helicoverpa zea* (Boddie) in sweet corn began with the discovery of sex pheromones in the 1970's (Cardé et al. 1975, Roelofs and Cardé 1977). The body of literature on chemical communication between male and female insects is extensive and many important discoveries of fundamental entomological and scientific importance have been made in the past 40 years. As knowledge grew, entomologists saw the usefulness of sex pheromones to advance pest management in agricultural systems. The understanding that pests such as *H. zea* have specific chemical communication pathways led to scientific discoveries and technical innovations that advanced pest management in fruit and vegetable production (Cardé and Minks 1995). The ability to attract males of a single pest species to a trap for observation was a breakthough and represented a plausible alternative to monitoring *H. zea* using black light traps, which indiscriminately attract a plethora of insect species representing multiple orders (Hartstack et al. 1973, Gauthier et al. 1991).

Pheromone trapping was first investigated as a management tool for *H. zea* in the 1980's. Research showed a strong correlation between numbers of males captured in pheromone traps and numbers of females detected in close proximity using both blacklight and net-trapping techniques (Chowdhury et al. 1987a, 1987b, Latheef et al. 1993). At the same time, synthetic pheromone production methods were also refined and became commercialized. In the late 1980s, integrated pest management (IPM) programs for sweet corn began using pheromone traps to monitor *H. zea* populations in order to determine when insecticide applications should be applied. These programs used catch threshold categories, each having a range of mean catch values over discrete periods when the sweet corn crop was vulnerable to H. zea attack. Based

on the moth catch thresholds, the application timing intervals varied with more frequent applications when moth catch was high and less frequent applications when moth catch was low. In the northeast United States, these guidelines are still used.

The concept of pheromone trapping as a way to indicate when control is needed is valid, but sweet corn is exceptionally vulnerable to infestation and a single caterpillar can cause complete economic loss of an ear of corn. For pheromone trapping to be used as a tool for making management decisions to avoid *H. zea* damage, the predictive ability of trapping must be very high. As demonstrated with predictive modeling techniques (thesis chapter 2), trap catch alone had the *lowest* predictive power of any single- or multiple-factor model tested. Pheromone trapping is very good at predicting pest pressure; however, trap catch *alone* is a very poor predictor of sweet corn *damage* caused by *H. zea* at harvest.

Pheromone trapping still has a role, but it must be considered in the broader context of additional factors that are also relevant to *H. zea* ovipositional behavior and larval development and successful infestation of the ear. Interactive effects between trap catch, lunar illumination, day-degree accumulation and rainfall have additive predictive effects, as the results in chapter 2 demonstrated. Most factors, used alone, had poor predictive power compared to a full-factorial predictive model.

In the 1980's, when IPM strategies for control of *H. zea* were first developed, the world wide web and mobile communication technologies were still in their infancy. The idea that a person could send or receive real-time data for the purposes of making rapid management decisions anywhere in the developed world was unheard of. Yet, that is exactly what has come to pass as of 2015. Information technologies and delivery mechanisms are already in place that have the potential to combine field-based pest observations with open-source environmental

datasets and server-side statistical models. Even 10 years ago, such an approach would have been tenuous at best. We now have the knowledge and capability to build new IPM tools that, from a growers' perspective, are easy to implement but also assimilate more complex calculations on servers. With one or two simple inputs, all other components can be remotely gathered or calculated to improve yield margins.

IPM is more important than ever in the 21st century, but treatment guidelines for control of *H. zea* haven't been updated in >25 years. As previously mentioned, pheromone trapping is sound approach for estimating population pressure. But, research presented in these thesis chapters demonstrates that decision-making processes for the mitigation of *H. zea* damage in sweet corn can benefit from a closer look at the nuanced interactions between insect pests, their host plants and the environment.

Trap catch is only useful in a broader context. The literature provides a number of interesting avenues for future research that can shed additional light on subtle, but important, interactions between female moths and the sweet corn plant host. Research first published in the 1970s, and again in the early 1990s, shows that silk volatiles have a strong role in host detection by female *H. zea* moths (Cantelo and Jacobson 1979, Raina et al. 1991). Noctuid moths are attracted to a suite of silk volatiles that include ethylene, which serves as a catalyst for sex pheromone production. Females also use plant volatiles after mating to find oviposition substrates.

These results are intriguing, but little else has been done to examine various aspects of this interaction between *H. zea* females and host volatiles. In the past 10 years, significant advances have been made in the wider field of plant-insect interactions, and such knowledge could lead to new discoveries. It is also interesting that basic entomological research has not

considered sweet corn and *H. zea* as a model system for the study of plant-insect interactions. Sweet corn is easily cultivated, fast-growing, and well-described. *H. zea* is known throughout North America, has been well-described in the literature and has been studied from a genetic perspective due to its propensity for pyrethroid resistance.

A better understanding of chemical communication pathways between *H. zea* and sweet corn would also be useful in an applied context. Research in this thesis shows that insecticide sprays applied during silking periods, when plants are most attractive for oviposition, could greatly improve sweet corn yield at harvest. For the grower, this translates to improved profit margins, reduced environmental impact and a better product for consumers.

Besides the attraction of silk for oviposition, other plant chemical attributes responsible for damage by *H. zea* deserve attention, and little has been done since the mid-1980s. For example, research at that time showed maysin, a compound found in corn silks, has a deleterious effect on *H. zea* larvae. Some researchers suggested it is a feeding deterrent while others indicated some level of direct toxicity. However, little else has been done to investigate the effects of maysin or other plant compounds that could influence infestation.

In 1998, the first sweet corn varieties expressing an insecticidal protein from *Bacillus thuringiensis* were commercialized in North America by Novartis Seeds, and these provide good control of *H. zea* (Shelton et al. 2013). Additional insecticidal proteins have been introduced to provide better control of *H. zea* and other Lepidoptera, but there is fear in the marketplace about backlash from consumers opposed to genetically engineered crops. Thus, there will continue to be need for traditional chemical insecticides applied in the most effective manner, including enhanced timing of application. As new pests enter the picture, such as western bean cutworm, *Striacosta albicosta* (Smith), further adjustments to pest management practices will be needed.

Finally, it must be noted that pyrethroids failed to achieve adequate control of *H. zea* in the experiments described here. Pyrethroid resistance is prevalent throughout the southern United States in cotton growing regions, from which annual progenitor populations of insects arriving in the northeast develop. As a result, there is some probability that *H. zea* infesting sweet corn in the northeast United States are also resistant to pyrethroids. Although this is not typically thought of as a problem outside of the cotton belt, results I have presented in my thesis suggest otherwise. Pyrethroid insecticides are inexpensive but did not achieve the desired control outcome. Therefore, it may be necessary at this point in time to start transitioning away from this group of chemistries as a treatment for *H. zea* in sweet corn.

Conclusions

Moving forward, IPM practices must keep pace with dynamic interactions that ultimately determine the probability of *H. zea* damage to sweet corn crops. In coming years, this will have increasing importance as climate change alters patterns of pest abundance and weather patterns. Such changes are no longer a matter of "if" but rather "when" and "how quickly?" (Oreskes 2004).

Pheromone trapping of adult male *H. zea* moths should continue to be a component of an IPM program for making control decisions for *H. zea* in sweet corn, but it should not be used as the sole predictor for determining the frequency of insecticide application or other curative management tactics. Other environmental and biological factors, including lunar illumination, insect developmental rate, crop stage, and precipitation influence damage outcomes as a result of larval infestation. Each of these need to be considered concurrently with pheromone trap catch information when predicting the risk levels of damage at harvest.

Tools and datasets are available to researchers that now allow a closer look at the way in which insect herbivores and crop hosts interact with each other and respond to environmental variables. A better understanding of plant-insect interactions within this system is also key to advancing management approaches to *H. zea* management in sweet corn. Future research of *H. zea* in sweet corn production systems should take a closer look at mechanisms of attraction between females and plant hosts.

Management of a polyphagous pest such as *H. zea* requires a broad knowledge-base that includes basic an applied research. Plant-insect interactions combined with environmental factors provide an understanding of when infestation is most likely. But, without an understanding of insecticide chemistries and modes of action the likelihood of successful control is reduced. Likewise, if a good insecticide is applied during a phase of plant development that is not suitable or attractive to the insect pest, efficacy will be reduced.

APPENDIX

Table S1. Polynomial equations calculated on a per-plant basis (n=106), using observed silk stage from first green silk to harvest to estimate day of year.

Year	Field	Plant ID	R^2	Polynomial function
2011	Gates	1	0.98	day of year = 247.2179 + 28.523421*silk stage - 21.013056*(silk stage-0.39444)^2
2011	Gates	2	0.98	day of year = 241.45437 + 26.629835*silk stage + 2.9114431*(silk stage-0.39375)^2
2011	Gates	3	0.98	day of year = 240.15626 + 30.46663*silk stage - 1.06031*(silk stage-0.425)^2
2011	Gates	4	0.98	day of year = 249.56225 + 32.998408*silk stage - 32.031588*(silk stage-0.31667)^2
2011	Gates	6	0.94	day of year = 246.52574 + 36.660101*silk stage - 22.756632*(silk stage-0.355)^2
2011	Gates	8	0.99	day of year = 241.67549 + 32.240378*silk stage - 16.124608*(silk stage-0.42727)^2
2011	Gates	9	0.99	day of year = 241.21567 + 33.196303*silk stage - 13.67194*(silk stage-0.41818)^2
2011	Gates	10	0.97	day of year = 248.1877 + 26.218808*silk stage - 12.868597*(silk stage-0.3625)^2
2011	Gates	11	0.98	day of year = 243.18238 + 23.785904*silk stage - 6.4001167*(silk stage-0.44)^2
2011	Gates	12	0.95	day of year = 252.29337 + 31.820065*silk stage - 36.710175*(silk stage-0.36111)^2
2011	Gates	13	0.98	day of year = 247.98894 + 35.590884*silk stage - 40.928187*(silk stage-0.35556)^2
2011	Gates	14	0.96	day of year = 243.07405 + 22.960308*silk stage - 22.362707*(silk stage-0.3875)^2
2011	Gates	15	0.98	day of year = 245.91335 + 35.123242*silk stage - 28.857981*(silk stage-0.35625)^2
2011	Gates	16	0.99	day of year = 251.34784 + 25.442092*silk stage - 18.210627*(silk stage-0.35)^2
2011	Gates	17	0.95	day of year = 247.2729 + 19.037769*silk stage - 0.8231321*(silk stage-0.44375)^2
2011	Gates	18	0.96	day of year = 250.98062 + 25.680779*silk stage - 22.681503*(silk stage-0.43889)^2
2011	Gates	20	0.97	day of year = 250.17386 + 29.913772*silk stage - 27.123208*(silk stage-0.38889)^2
2011	North	1	0.98	day of year = 244.78419 + 28.462832*silk stage - 25.680765*(silk stage-0.34375)^2
2011	North	2	0.98	day of year = 251.06619 + 30.060212*silk stage - 29.839587*(silk stage-0.38889)^2
2011	North	3	0.98	day of year = 249.56225 + 32.998408*silk stage - 32.031588*(silk stage-0.31667)^2
2011	North	4	0.97	day of year = 249.84072 + 27.029501*silk stage - 23.528564*(silk stage-0.36667)^2
2011	North	7	0.96	day of year = 250.26677 + 30.296458*silk stage - 29.417127*(silk stage-0.39444)^2
2011	North	8	0.97	day of year = 247.37555 + 33.064784*silk stage - 36.214014*(silk stage-0.32857)^2
2011	North	9	0.98	day of year = 249.1742 + 27.974622*silk stage - 22.087656*(silk stage-0.3625)^2
2011	North	11	0.99	day of year = 242.33007 + 21.406501*silk stage - 4.5979594*(silk stage-0.45)^2
2011	North	12	0.96	day of year = 250.07658 + 25.028597*silk stage - 20.823615*(silk stage-0.39375)^2
2011	North	13	0.98	day of year = 246.74801 + 27.109846*silk stage - 21.358355*(silk stage-0.35556)^2
2011	North	15	0.98	day of year = 252.07561 + 30.707675*silk stage - 17.148478*(silk stage-0.38889)^2
2011	North	17	0.95	day of year = 233.40688 + 20.799594*silk stage + 18.199496*(silk stage-0.57857)^2
2011	North	18	0.98	day of year = 247.74972 + 32.048586*silk stage - 30.45724*(silk stage-0.31875)^2
2011	North	19	0.99	day of year = 239.38759 + 24.267646*silk stage + 0.3916445*(silk stage-0.47222)^2
2011	North	20	0.99	day of year = 244.43768 + 25.916956*silk stage - 3.8677693*(silk stage-0.45)^2
2011	South	1	0.98	day of year = 254.96683 + 32.186286*silk stage - 23.637951*(silk stage-0.32222)^2
2011	South	2	0.97	day of year = 249.25429 + 36.67761*silk stage - 37.069315*(silk stage-0.3)^2
2011	South	3	0.93	day of year = 254.38802 + 28.920488*silk stage - 27.930675*(silk stage-0.39444)^2
2011	South	5	0.94	day of year = 246.49672 + 17.482211*silk stage - 9.9323767*(silk stage-0.4375)^2
2011	South	6	0.97	day of year = 250.91564 + 33.23231*silk stage - 27.900543*(silk stage-0.4)^2
2011	South	7	0.92	day of year = 256.5126 + 27.559663*silk stage - 23.213525*(silk stage-0.3625)^2
2011	South	8	0.97	day of year = 250.82724 + 23.002807*silk stage - 9.5587219*(silk stage-0.45)^2
2011	South	11	0.95	day of year = 250.02316 + 15.802043*silk stage - 0.845128*(silk stage-0.45714)^2
2011	South	12	0.97	day of year = 250.48277 + 30.890613*silk stage - 18.288868*(silk stage-0.41111)^2
2011	South	13	0.95	day of year = 251.64177 + 32.553263*silk stage - 27.412687*(silk stage-0.38889)^2
2011	South	14	0.96	day of year = 247.34129 + 23.79739*silk stage - 0.373484*(silk stage-0.475)^2
2011	South	15	0.98	day of year = 247.98811 + 21.501964*silk stage - 9.4038462*(silk stage-0.4)^2
2011	South	16	0.99	day of year = 249.81267 + 20.342659*silk stage - 4.402861*(silk stage-0.45625)^2
2011	South	17	0.98	day of year = 249.86867 + 27.219055*silk stage - 3.0800818*(silk stage-0.45)^2
2011	South	18	0.92	day of year = 251.71891 + 28.520123*silk stage - 31.643923*(silk stage-0.34375)^2
2011	South	20	0.98	day of year = 254.34867 + 18.624255*silk stage - 15.06986*(silk stage-0.40714)^^{2}
2012	Gates	2	0.98	day of year = 238 + 18.059701*silk stage
2012	Gates	3	0.94	day of year = 238 + 18.059701*silk stage
2012	Gates	5	0.98	day of year = 238 + 18.059701*silk stage
2012	Gates	6	0.94	day of year = 239 + 16.917808*silk stage
2012	Gates	7	0.98	day of year = 238 + 18.059701*silk stage
2012	Gates	8	0.99	day of year = 236.4 + 19.016393*silk stage
2012	Gates	11	0.93	day of year = 239 + 16.917808*silk stage
2012	Gates	12	0.94	day of year = 239 + 16.917808*silk stage
2012	Gates	13	0.98	day of year = 238 + 18.059701*silk stage
2012	Gates	14	0.91	day of year = 239.5 + 16.254072*silk stage
2012	Gates	15	0.94	day of year = 239 + 16.917808*silk stage
2012	Gates	16	0.94	day of year = 239 + 16.917808*silk stage
2012	Gates	17	0.91	day of year = 239.5 + 16.254072*silk stage

2012	Gates	18	0.91	day of year = 238.6 + 17.252747*silk stage
2012	Gates	19	0.91	day of year = 239.5 + 16.254072*silk stage
2012	Gates	20	0.94	day of year = 239 + 16.917808*silk stage
2012	Gates	21	0.94	day of year = 239 + 16.917808*silk stage
2012	Gates	22	0.94	day of year = 239 + 16.917808*silk stage
2012	Gates	23	0.96	day of year = 238.5 + 17.526882*silk stage
2012	Gates	24	0.98	day of year = 238 + 18.059701*silk stage
2012	Gates	25	0.98	day of year = 238 + 18.059701*silk stage
2012	North	1	0.99	day of year = 242.9 + 22.014925*silk stage
2012	North	2	0.99	day of year = 242.9 + 22.014925*silk stage
2012	North	3	0.98	day of year = 242.8 + 20.890411*silk stage
2012	North	5	0.98	day of year = 242.8 + 20.890411*silk stage
2012	North	6	0.79	day of year = 246.5 + 20.238095*silk stage
2012	North	7	0.88	day of year = 245.2 + 21.721311*silk stage
2012	North	8	0.98	day of year = 242.8 + 20.890411*silk stage
2012	North	9	0.98	day of year = 242.8 + 20.890411*silk stage
2012	North	10	0.99	day of year = 243.3 + 22.619048*silk stage
2012	North	11	0.99	day of year = 242.9 + 22.014925*silk stage
2012	North	12	1.00	day of year = 243 + 16.666667*silk stage
2012	North	13	0.99	day of year = 242.9 + 22.014925*silk stage
2012	North	14	0.89	day of year = 245.2 + 21.721311*silk stage
2012	North	15	0.98	day of year = 242.8 + 20.890411*silk stage
2012	North	16	0.98	day of year = 242.8 + 20.890411*silk stage
2012	North	17	1.00	day of year = 243 + 16.666667*silk stage
2012	North	18	0.99	day of year = 242.9 + 22.014925*silk stage
2012	North	19	0.98	day of year = 242.8 + 20.890411*silk stage
2012	North	20	1.00	day of year = 243 + 16.666667*silk stage
2012	North	21	0.98	day of year = 242.8 + 20.890411*silk stage
2012	North	22	0.99	day of year = 243.3 + 22.619048*silk stage
2012	North	23	0.98	day of year = 242.8 + 20.890411*silk stage
2012	North	24	0.98	day of year = 242.8 + 20.890411*silk stage
2012	North	25	0.98	day of year = 242.8 + 20.890411*silk stage
2012	South	2	0.98	day of year = 242.1 + 27.540984*silk stage
2012	South	5	0.98	day of year = 244.1 + 27.142857*silk stage
2012	South	7	0.88	day of year = 247 + 23.835616*silk stage
2012	South	8	0.98	day of year = 242.1 + 27.540984*silk stage
2012	South	10	0.77	day of year = 242.3 + 22.39726*silk stage
2012	South	11	0.86	day of year = 241.8 + 24.626866*silk stage
2012	South	12	0.99	day of year = 242.9 + 27.786885*silk stage
2012	South	13	0.99	day of year = 244.1 + 27.142857*silk stage
2012	South	14	0.86	day of year = 241.8 + 24.626866*silk stage
2012	South	15	0.73	day of year = 242.6 + 21.205212*silk stage
2012	South	16	0.86	day of year = 241.8 + 24.626866*silk stage
2012	South	20	0.94	day of year = 245.5 + 25.746269*silk stage
2012	South	21	0.86	day of year = 241.8 + 24.626866*silk stage
2012	South	22	0.98	day of year = 242.1 + 27.540984*silk stage
2012	South	23	0.94	day of year = 245.5 + 25.746269*silk stage
2012	South	24	0.99	day of year = 242.9 + 27.786885*silk stage
2012	South	25	0.86	day of year = 241.8 + 24.626866*silk stage

Table S2. Polynomial equations calculated from environmental data versus day of year for *Helicoverpa zea* trap catch accumulation (TC), lunar illumination (I), *H. zea* base-12.5°C day-degree accumulation (T) and precipitation (mm) accumulation (P).

Parameter	Year	Field	R^2	polynomial function
TC	2011	Gates	0.99	-1700.351 + 7.0564304*day of year + 0.0026827*(day of year-251.867)^2 - 0.0094816*(day of year-251.867)^3
		North	0.99	-2673.668 + 11.107382*day of year + 0.0149284*(day of year-250.429)^2 - 0.0184265*(day of year-250.429)^3
		South	0.99	-1599.767 + 6.6615186*day of year + 0.0255229*(day of year-250.429)^2 - 0.0086047*(day of year-250.429)^3
	2012	Gates	0.97	-270.2063 + 1.1479821*day of year
		North	0.99	-186.5231 + 0.7769231*day of year
		South	0.93	-55.76221 + 0.2356688*day of year
I	2011	-	0.99	1.0554066 - 0.0003819*day of year - 0.0074846*(day of year-255.143)^2 + 4.376e-6*(day of year-255.143)^3 + 1.3521e-5*(day of year-255.143)^4
	2012	-	0.98	1.1507146 - 0.0009357*day of year - 0.0071766*(day of year-244.429)^2 + 1.163e-5*(day of year-244.429)^3 + 1.3051e-5*(day of year-244.429)^4
T	2011	-	0.99	-1250.377+5.6740302*day of year – 0.0692837*(day of year-250.5)^2
	2012	-	0.99	-1382.233+6.2124769*day of year – 0.12306*(day of year-252)^2
P	2011	-	0.97	-829.0901 + 3.8647406*day of year - 0.0060513*(day of year-250.5)^2 - 0.0012822*(day of year-250.5)^3
	2012	-	0.95	-431.9356 + 1.8336729*day of year + 0.015066*(day of year-252)^2 - 0.0000408*(day of year-252)

Table S3. Dataset of Δ in factor values of accumulated trap catch (TC), lunar illumination (I), accumulated *H. zea* base-12.5°C day-degrees (T) and accumulated precipitation in mm (P) for sweet corn phenological phases of first green silk to 25% dry silk (ΔGS-25%), 25% dry silk to 50% dry silk (Δ25-50%), 50% dry silk to harvest (Δ50%-H) and first green silk to harvest (ΔGS-H)

year	farm	plotID	GS	25%	50%	H	Δ TC GS-25%	Δ TC 25-50%	Δ TC 50%-H	Δ TC GS to H	Δ I GS-25%	Δ I 25-50%	Δ I 50%-H	Δ I GS to H	Δ T GS-25%	Δ T 25-50%	Δ T 50%-H	Δ T GS to H	Δ P GS-25%	Δ P 25-50%	Δ P 50-%H	Δ P GS to H	state
2011	Gates	1	247	254	261	267	51.9	34.7	15.5	102.1	0.41	-0.21	-0.55	-0.35	39.1	30.7	23.5	93.4	26.6	23.3	18.4	68.4	damaged
2011	Gates	2	241	248	255	262	24.2	26.7	29.1	80.0	0.60	0.33	-0.30	0.64	43.2	37.3	31.2	111.8	25.3	25.8	23.9	75.1	damaged
2011	Gates	3	240	248	255	263	42.9	41.3	37.1	121.3	0.59	0.37	-0.40	0.56	50.0	41.9	33.9	125.8	28.6	29.0	26.1	83.7	damaged
2011	Gates	4	250	258	265	273	93.7	36.5	0.0	109.4	0.17	-0.58	-0.33	-0.74	42.2	31.8	22.7	96.7	30.3	24.9	16.8	72.0	damaged
2011	Gates	6	247	256	264	272	85.4	45.6	5.2	136.2	0.48	-0.52	-0.44	-0.48	50.3	37.8	26.6	114.7	34.4	29.2	19.9	83.6	damaged
2011	Gates	8	242	250	257	264	51.7	46.3	32.0	130.0	0.70	0.19	-0.50	0.40	50.0	39.7	30.5	120.2	30.0	28.4	23.8	82.1	damaged
2011	Gates	9	241	249	257	265	51.6	46.2	32.1	129.9	0.72	0.20	-0.54	0.37	52.1	41.5	31.9	125.5	31.0	29.7	24.9	85.5	damaged
2011	Gates	10	248	255	261	267	63.2	36.8	10.5	110.4	0.33	-0.23	-0.54	-0.44	35.8	29.1	23.0	87.9	24.7	22.2	18.1	65.0	clean
2011	Gates	11	243	249	255	260	46.6	38.9	31.1	116.6	0.54	0.26	-0.19	0.60	36.9	31.3	26.1	94.3	22.5	21.9	19.9	64.2	damaged
2011	Gates	12	252	260	267	273	66.9	35.5	4.0	106.4	-0.11	-0.62	-0.18	-0.90	37.5	27.4	19.0	83.8	28.0	21.5	13.6	63.1	damaged
2011	Gates	13	248	257	264	272	62.7	39.7	10.1	112.5	0.33	-0.54	-0.41	-0.61	46.5	34.0	23.5	104.0	32.6	26.4	17.7	76.8	damaged
2011	Gates	14	243	249	254	258	36.2	32.0	27.8	96.0	0.51	0.28	-0.06	0.75	35.0	28.5	23.0	86.5	21.1	19.6	17.2	58.0	clean
2011	Gates	15	246	254	263	270	36.7	23.4	9.6	69.7	0.54	-0.37	-0.59	-0.42	48.9	36.9	26.5	112.4	32.8	28.3	20.5	81.6	clean
2011	Gates	16	251	258	264	269	58.6	34.2	9.9	102.7	0.06	-0.41	-0.48	-0.84	31.9	25.4	19.7	77.0	23.3	19.9	15.3	58.4	clean
2011	Gates	17	247	252	257	261	45.6	34.0	22.3	101.9	0.34	0.05	-0.26	0.13	27.5	24.3	21.1	72.9	18.3	17.7	16.3	52.4	damaged
2011	Gates	18	251	257	263	268	60.2	33.8	7.5	101.5	0.09	-0.36	-0.46	-0.72	31.9	24.5	18.3	74.7	23.1	19.0	14.3	56.5	clean
2011	Gates	20	250	257	264	270	57.8	28.9	0.0	86.6	0.14	-0.48	-0.44	-0.78	37.7	28.5	20.8	87.0	27.2	22.3	15.9	65.4	damaged
2011	North	1	245	252	258	264	97.0	68.6	40.1	205.7	0.56	0.01	-0.47	0.10	41.5	33.1	25.7	100.3	26.7	24.3	20.1	71.2	damaged
2011	North	2	251	258	265	271	106.7	61.4	16.1	184.2	0.05	-0.52	-0.36	-0.84	36.8	27.6	19.8	84.2	27.0	21.6	15.0	63.5	damaged
2011	North	3	250	258	265	273	130.9	73.1	15.3	219.2	0.17	-0.58	-0.33	-0.74	42.2	31.8	22.7	96.7	30.3	24.9	16.8	72.0	clean
2011	North	4	250	256	263	268	115.9	69.4	23.0	208.3	0.19	-0.36	-0.52	-0.69	34.8	27.3	20.8	82.9	24.9	21.1	16.2	62.2	damaged
2011	North	7	250	258	264	270	104.3	58.6	12.9	175.8	0.13	-0.49	-0.43	-0.79	37.9	28.4	20.5	86.8	27.4	22.2	15.7	65.3	damaged
2011	North	8	247	255	263	270	95.6	55.3	15.1	166.0	0.40	-0.40	-0.55	-0.56	44.5	33.7	24.4	102.6	30.7	26.0	18.8	75.5	damaged
2011	North	9	249	256	262	269	93.3	55.7	18.2	167.2	0.24	-0.36	-0.54	-0.65	36.7	28.8	21.9	87.4	25.9	22.3	17.1	65.2	clean
2011	North	11	242	248	253	258	60.6	58.2	55.8	174.6	0.49	0.34	-0.02	0.81	34.1	29.6	25.3	89.0	20.1	20.0	18.7	58.8	damaged
2011	North	12	250	256	262	267	95.3	56.9	18.5	170.6	0.17	-0.30	-0.48	-0.60	32.2	25.4	19.7	77.3	23.0	19.6	15.4	58.0	clean
2011	North	13	247	253	260	266	108.8	72.0	35.2	216.0	0.44	-0.12	-0.51	-0.19	37.9	30.4	23.7	92.0	25.5	22.8	18.6	66.9	damaged
2011	North	15	252	260	267	274	88.8	41.3	0.0	123.9	-0.08	-0.62	-0.19	-0.89	37.1	28.2	20.2	85.4	27.6	22.1	14.5	64.2	damaged
2011	North	17	233	239	245	252	0.0	20.7	61.9	62.0	-0.40	0.36	0.54	0.50	42.7	43.3	41.9	127.9	18.1	23.3	27.4	68.8	clean
2011	North	18	248	256	263	270	127.7	77.4	27.1	232.1	0.37	-0.41	-0.55	-0.59	43.1	33.1	24.3	100.6	29.9	25.6	18.8	74.2	damaged
2011	North	19	239	245	252	258	40.0	54.7	69.3	164.0	0.37	0.49	0.05	0.91	41.3	36.2	31.1	108.6	22.4	23.5	22.8	68.7	damaged
2011	North	20	244	251	257	263	90.5	70.4	50.2	211.1	0.55	0.10	-0.42	0.23	39.0	32.8	26.9	98.7	24.8	23.8	20.9	69.5	clean
2011	South	1	255	263	270	278	54.8	29.7	4.6	89.0	-0.40	-0.56	0.70	-0.26	35.6	26.1	17.5	79.2	27.4	20.1	10.3	57.7	damaged
2011	South	2	249	258	267	275	72.3	39.5	6.7	118.5	0.17	-0.69	-0.08	-0.60	46.8	34.3	23.2	104.3	33.7	26.8	16.3	76.8	damaged
2011	South	3	254	261	268	274	59.7	31.1	2.5	93.4	-0.27	-0.58	-0.11	-0.95	32.4	23.9	16.9	73.2	24.7	18.7	12.0	55.4	damaged
2011	South	5	246	251	255	259	44.7	34.2	23.6	102.5	0.35	0.14	-0.08	0.40	25.2	21.5	18.2	65.0	16.4	15.3	13.7	45.5	damaged
2011	South	6	251	259	266	273	65.3	34.6	3.9	103.9	0.02	-0.62	-0.23	-0.83	40.6	29.8	20.7	91.1	29.8	23.3	15.0	68.1	damaged
2011	South	7	257	263	270	275	40.4	21.4	2.3	64.1	-0.42	-0.53	0.20	-0.74	29.3	22.0	15.6	66.9	22.8	17.0	10.2	50.0	damaged
2011	South	8	251	256	262	267	58.7	37.7	16.7	113.0	0.12	-0.30	-0.47	-0.65	29.5	24.1	19.3	72.9	21.3	18.6	15.1	55.0	damaged
2011	South	11	250	254	258	262	36.4	28.4	20.4	85.1	0.18	-0.05	-0.25	-0.12	21.5	19.3	17.1	57.9	15.1	14.4	13.3	42.8	damaged
2011	South	13	252	260	267	274	65.6	33.9	2.3	101.8	-0.05	-0.63	-0.18	-0.86	39.2	28.8	20.0	88.0	29.0	22.6	14.4	65.9	damaged
2011	South	15	248	253	258	263	54.5	38.7	22.9	116.1	0.32	-0.05	-0.36	-0.09	29.9	25.1	20.8	75.8	20.3	18.7	16.3	55.4	damaged
2011	South	16	250	255	260	265	47.1	34.0	21.0	102.1	0.20	-0.15	-0.40	-0.36	27.3	23.3	19.5	70.0	19.2	17.7	15.3	52.2	damaged
2011	South	17	250	257	263	270	60.3	38.5	16.6	115.4	0.18	-0.42	-0.52	-0.76	35.8	29.2	22.7	87.7	25.6	22.6	17.5	65.8	clean
2011	South	20	254	259	263	267	45.8	28.1	10.4	84.3	-0.10	-0.31	-0.36	-0.77	21.7	17.7	14.2	53.6	16.4	13.9	11.1	41.4	clean
2012	Gates	2	238	243	247	252	5.0	5.2	5.4	15.7	0.25	-0.03	-0.28	-0.06	41.1	36.1	31.1	108.2	6.6	7.3	7.9	21.8	clean
2012	Gates	3	238	243	247	252	9.1	6.2	3.2	18.5	0.25	-0.03	-0.28	-0.06	41.1	36.1	31.1	108.2	6.6	7.3	7.9	21.8	clean
2012	Gates	5	238	243	247	252	5.0	5.2	5.4	15.7	0.25	-0.03	-0.28	-0.06	41.1	36.1	31.1	108.2	6.6	7.3	7.9	21.8	clean
2012	Gates	6	239	243	247	252	9.1	6.2	3.2	18.5	0.19	-0.06	-0.28	-0.15	37.6	33.2	28.8	99.6	6.3	6.9	7.4	20.6	clean
2012	Gates	7	238	243	247	252	5.0	5.2	5.4	15.7	0.25	-0.03	-0.28	-0.06	41.1	36.1	31.1	108.2	6.6	7.3	7.9	21.8	clean
2012	Gates	8	236	241	246	251	1.7	4.4	7.2	13.3	0.33	0.06	-0.25	0.14	45.0	39.4	33.9	118.3	6.7	7.5	8.2	22.4	clean
2012	Gates	11	239	243	247	252	9.1	6.2	3.2	18.5	0.19	-0.06	-0.28	-0.15	37.6	33.2	28.8	99.6	6.3	6.9	7.4	20.6	clean
2012	Gates	12	239	243	247	252	9.1	6.2	3.2	18.5	0.19	-0.06	-0.28	-0.15	37.6	33.2	28.8	99.6	6.3	6.9	7.4	20.6	clean
2012	Gates	13	238	243	247	252	5.0	5.2	5.4	15.7	0.25	-0.03	-0.28	-0.06	41.1	36.1	31.1	108.2	6.6	7.3	7.9	21.8	clean
2012	Gates	14	240	244	248	252	16.5	7.9	0.0	23.6	0.16	-0.07	-0.27	-0.18	35.7	31.6	27.6	94.9	6.1	6.6	7.2	19.9	clean
2012	Gates	15	239	243	247	252	9.1	6.2	3.2	18.5	0.19	-0.06	-0.28	-0.15	37.6	33.2	28.8	99.6	6.3	6.9	7.4	20.6	clean
2012	Gates	16	239	243	247	252	9.1	6.2	3.2	18.5	0.19	-0.06	-0.28	-0.15	37.6	33.2	28.8	99.6	6.3	6.9	7.4	20.6	clean
2012	Gates	17	240	244	248	252	16.5	7.9	0.0	23.6	0.16	-0.07	-0.27	-0.18	35.7	31.6	27.6	94.9	6.1	6.6	7.2	19.9	clean
2012	Gates	18	239	243	247	252	16.8	9.2	0.2	26.2	0.21	-0.04	-0.27	-0.11	38.7	34.2	29.6	102.5	6.4	7.0	7.6	20.9	clean
2012	Gates	19	240	244	248	252	16.5	7.9	0.0	23.6	0.16	-0.07	-0.27	-0.18	35.7	31.6	27.6	94.9	6.1	6.6	7.2	19.9	clean
2012	Gates	20	239	243	247	252	9.1	6.2	3.2	18.5	0.19	-0.06	-0.28	-0.15	37.6	33.2	28.8	99.6	6.3	6.9	7.4	20.6	clean
2012	Gates	21	239	243	247	252	9.1	6.2	3.2	18.5	0.19	-0.06	-0.28	-0.15	37.6	33.2	28.8	99.6	6.3	6.9	7.4	20.6	clean
2012	Gates	22	239	243	247	252	9.1	6.2	3.2	18.5	0.19	-0.06	-0.28	-0.15	37.6	33.2	28.8	99.6	6.3	6.9	7.4	20.6	clean
2012	Gates	23	239	243	247	252	6.5	5.6	4.6	16.7	0.22	-0.04	-0.28	-0.11	39.4	34.7	30.0	104.1	6.5	7.1	7.7	21.3	clean
2012	Gates	24	238	243	247	252	5.0	5.2	5.4	15.7	0.25	-0.03	-0.28	-0.06	41.1	36.1	31.1	108.2	6.6	7.3	7.9	21.8	clean
2012	Gates	25	238	243	247	252	5.0	5.2	5.4	15.7	0.25	-0.03	-0.28	-0.06	41.1	36.1	31.1	108.2	6.6	7.3	7.9	21.8	clean
2012	North	1	243	248	254	259	5.7	4.5	3.3	13.6	-0.10	-0.43	-0.38	-0.91	42.8	35.3	27.9	106.0	9.0	9.9	10.8	29.8	clean
2012	North	2	243	248	254	259	5.7	4.5	3.3	13.6	-0.10	-0.43	-0.38	-0.91	42.8	35.3	27.9	106.0	9.0	9.9	10.8	29.8	damaged
2012	North	3	243	248	253	258	3.5	4.0	4.5	12.0	-0.08	-0.39	-0.41	-0.87	40.9	34.2	27.5	102.6	8.5	9.4	10.2	28.0	clean
2012	North	5	243	248	253	258	3.5	4.0	4.5	12.0	-0.08	-0.39	-0.41	-0.87	40.9	34.2	27.5	102.6	8.5	9.4	10.2	28.0	clean
2012	North	6	247	252	257	262	11.4	5.8	0.3	17.5	-0.30	-0.43	-0.15	-0.89	35.1	28.8	22.5	86.5	8.8	9.6	10.3	28.7	clean
2012	North	7	245	251	256	261	9.3	5.4	1.4	16.1	-0.25	-0.46	-0.20	-0.92	39.2	31.9	24.7	95.8	9.3	10.2	11.0	30.5	clean

2012	North	8	243	248	253	258	3.5	4.0	4.5	12.0	-0.08	-0.39	-0.41	-0.87	40.9	34.2	27.5	102.6	8.5	9.4	10.2	28.0	damaged
2012	North	9	243	248	253	258	3.5	4.0	4.5	12.0	-0.08	-0.39	-0.41	-0.87	40.9	34.2	27.5	102.6	8.5	9.4	10.2	28.0	clean
2012	North	10	243	249	255	260	6.9	4.8	2.7	14.4	-0.14	-0.46	-0.32	-0.91	43.3	35.4	27.6	106.3	9.3	10.3	11.3	30.9	clean
2012	North	11	243	248	254	259	5.7	4.5	3.3	13.6	-0.10	-0.43	-0.38	-0.91	42.8	35.3	27.9	106.0	9.0	9.9	10.8	29.8	clean
2012	North	12	243	247	251	256	3.6	3.6	3.6	10.8	-0.04	-0.26	-0.36	-0.66	33.0	28.7	24.4	86.1	6.7	7.3	7.8	21.9	clean
2012	North	13	243	248	254	259	5.7	4.5	3.3	13.6	-0.10	-0.43	-0.38	-0.91	42.8	35.3	27.9	106.0	9.0	9.9	10.8	29.8	clean
2012	North	14	245	251	256	261	9.3	5.4	1.4	16.1	-0.25	-0.46	-0.20	-0.92	39.2	31.9	24.7	95.8	9.3	10.2	11.0	30.5	damaged
2012	North	15	243	248	253	258	3.5	4.0	4.5	12.0	-0.08	-0.39	-0.41	-0.87	40.9	34.2	27.5	102.6	8.5	9.4	10.2	28.0	clean
2012	North	16	243	248	253	258	3.5	4.0	4.5	12.0	-0.08	-0.39	-0.41	-0.87	40.9	34.2	27.5	102.6	8.5	9.4	10.2	28.0	clean
2012	North	17	243	247	251	256	3.6	3.6	3.6	10.8	-0.04	-0.26	-0.36	-0.66	33.0	28.7	24.4	86.1	6.7	7.3	7.8	21.9	clean
2012	North	18	243	248	254	259	5.7	4.5	3.3	13.6	-0.10	-0.43	-0.38	-0.91	42.8	35.3	27.9	106.0	9.0	9.9	10.8	29.8	clean
2012	North	19	243	248	253	258	3.5	4.0	4.5	12.0	-0.08	-0.39	-0.41	-0.87	40.9	34.2	27.5	102.6	8.5	9.4	10.2	28.0	damaged
2012	North	20	243	247	251	256	3.6	3.6	3.6	10.8	-0.04	-0.26	-0.36	-0.66	33.0	28.7	24.4	86.1	6.7	7.3	7.8	21.9	clean
2012	North	21	243	248	253	258	3.5	4.0	4.5	12.0	-0.08	-0.39	-0.41	-0.87	40.9	34.2	27.5	102.6	8.5	9.4	10.2	28.0	clean
2012	North	22	243	249	255	260	6.9	4.8	2.7	14.4	-0.14	-0.46	-0.32	-0.91	43.3	35.4	27.6	106.3	9.3	10.3	11.3	30.9	damaged
2012	North	23	243	248	253	258	3.5	4.0	4.5	12.0	-0.08	-0.39	-0.41	-0.87	40.9	34.2	27.5	102.6	8.5	9.4	10.2	28.0	clean
2012	North	24	243	248	253	258	3.5	4.0	4.5	12.0	-0.08	-0.39	-0.41	-0.87	40.9	34.2	27.5	102.6	8.5	9.4	10.2	28.0	clean
2012	North	25	243	248	253	258	3.5	4.0	4.5	12.0	-0.08	-0.39	-0.41	-0.87	40.9	34.2	27.5	102.6	8.5	9.4	10.2	28.0	clean
2012	South	2	242	249	256	263	2.2	1.8	1.4	5.4	-0.11	-0.56	-0.17	-0.85	53.7	42.0	30.4	126.1	11.2	12.7	14.1	38.1	clean
2012	South	5	244	251	258	264	3.5	2.1	0.7	6.3	-0.28	-0.56	0.14	-0.70	49.7	38.4	27.0	115.1	11.5	12.9	14.2	38.6	clean
2012	South	7	247	253	259	265	8.4	3.2	0.0	9.7	-0.40	-0.46	0.27	-0.59	40.0	31.2	22.5	93.7	10.6	11.6	12.6	34.8	clean
2012	South	8	242	249	256	263	2.2	1.8	1.4	5.4	-0.11	-0.56	-0.17	-0.85	53.7	42.0	30.4	126.1	11.2	12.7	14.1	38.1	damaged
2012	South	10	242	248	253	259	0.0	1.0	3.1	3.1	-0.06	-0.41	-0.42	-0.89	44.3	36.6	28.9	109.7	9.1	10.0	11.0	30.1	clean
2012	South	11	242	248	254	260	0.9	1.5	2.1	4.5	-0.04	-0.47	-0.37	-0.88	49.0	39.7	30.4	119.1	9.9	11.1	12.2	33.3	clean
2012	South	12	243	250	257	264	2.7	1.9	1.1	5.7	-0.19	-0.58	-0.01	-0.78	52.8	40.9	29.0	122.7	11.5	13.0	14.4	38.9	damaged
2012	South	13	244	251	258	264	3.5	2.1	0.7	6.3	-0.28	-0.56	0.14	-0.70	49.7	38.4	27.0	115.1	11.5	12.9	14.2	38.6	clean
2012	South	14	242	248	254	260	0.9	1.5	2.1	4.5	-0.04	-0.47	-0.37	-0.88	49.0	39.7	30.4	119.1	9.9	11.1	12.2	33.3	clean
2012	South	16	242	248	254	260	0.9	1.5	2.1	4.5	-0.04	-0.47	-0.37	-0.88	49.0	39.7	30.4	119.1	9.9	11.1	12.2	33.3	clean
2012	South	20	246	252	258	265	4.8	2.4	0.0	7.1	-0.36	-0.52	0.23	-0.64	45.2	35.0	24.8	105.0	11.2	12.4	13.6	37.1	clean
2012	South	21	242	248	254	260	0.9	1.5	2.1	4.5	-0.04	-0.47	-0.37	-0.88	49.0	39.7	30.4	119.1	9.9	11.1	12.2	33.3	clean
2012	South	22	242	249	256	263	2.2	1.8	1.4	5.4	-0.11	-0.56	-0.17	-0.85	53.7	42.0	30.4	126.1	11.2	12.7	14.1	38.1	clean
2012	South	23	246	252	258	265	4.8	2.4	0.0	7.1	-0.36	-0.52	0.23	-0.64	45.2	35.0	24.8	105.0	11.2	12.4	13.6	37.1	clean
2012	South	24	243	250	257	264	2.7	1.9	1.1	5.7	-0.19	-0.58	-0.01	-0.78	52.8	40.9	29.0	122.7	11.5	13.0	14.4	38.9	clean
2012	South	25	242	248	254	260	0.9	1.5	2.1	4.5	-0.04	-0.47	-0.37	-0.88	49.0	39.7	30.4	119.1	9.9	11.1	12.2	33.3	clean

Table S4. (a) Nominal logistic regression equation and (b) damage probability equation for sweet corn during the reproductive phase beginning at 1st detected green silk and ending at 25% dry silk using lunar illumination (I), *Helicoverpa zea* day-degrees (T), and precipitation (P).

(a) Lin[clean] =

$$
\begin{aligned}
&6.90071653737042 \\
&+ -4.0188464380196 * \Delta I\ GS\text{-}25 \\
&+ -0.1195114179611 * \Delta T\ GS\text{-}25 \\
&+ \left(\Delta I\ GS\text{-}25 - 0.09126380243007\right) * \left(\left(\Delta T\ GS\text{-}25 - 40.1986356910717\right) * 0.1425679318168\right) \\
&+ 0.06393795805928 * \Delta P\ GS\text{-}25 \\
&+ \left(\Delta I\ GS\text{-}25 - 0.09126380243007\right) * \left(\left(\Delta P\ GS\text{-}25 - 15.6265750870879\right) * 0.47688758500408\right) \\
&+ \left(\Delta T\ GS\text{-}25 - 40.1986356910717\right) * \left(\left(\Delta P\ GS\text{-}25 - 15.6265750870879\right) * 0.0132721397938\right) \\
&+ \left(\Delta I\ GS\text{-}25 - 0.09126380243007\right) * \left(\left(\Delta T\ GS\text{-}25 - 40.1986356910717\right) * \left(\left(\Delta P\ GS\text{-}25 - 15.6265750870879\right) * -0.0372007707519\right)\right) \\
&+ -0.1238154784132 * \Delta TC\ GS\text{-}25 \\
&+ \left(\Delta I\ GS\text{-}25 - 0.09126380243007\right) * \left(\left(\Delta TC\ GS\text{-}25 - 31.5677906486595\right) * -0.26203877829\right) \\
&+ \left(\Delta T\ GS\text{-}25 - 40.1986356910717\right) * \left(\left(\Delta TC\ GS\text{-}25 - 31.5677906486595\right) * -0.0020851996159\right) \\
&+ \left(\Delta I\ GS\text{-}25 - 0.09126380243007\right) * \left(\left(\Delta T\ GS\text{-}25 - 40.1986356910717\right) * \left(\left(\Delta TC\ GS\text{-}25 - 31.5677906486595\right) * 0.01603021439662\right)\right) \\
&+ \left(\Delta P\ GS\text{-}25 - 15.6265750870879\right) * \left(\left(\Delta TC\ GS\text{-}25 - 31.5677906486595\right) * 0.00791824052488\right) \\
&+ \left(\Delta I\ GS\text{-}25 - 0.09126380243007\right) * \left(\left(\Delta P\ GS\text{-}25 - 15.6265750870879\right) * \left(\left(\Delta TC\ GS\text{-}25 - 31.5677906486595\right) * 0.03307602978245\right)\right) \\
&+ \left(\Delta T\ GS\text{-}25 - 40.1986356910717\right) * \left(\left(\Delta P\ GS\text{-}25 - 15.6265750870879\right) * \left(\left(\Delta TC\ GS\text{-}25 - 31.5677906486595\right) * -0.0006641322436\right)\right) \\
&+ \left(\Delta I\ GS\text{-}25 - 0.09126380243007\right) * \left(\left(\Delta T\ GS\text{-}25 - 40.1986356910717\right) * \left(\left(\Delta P\ GS\text{-}25 - 15.6265750870879\right) * \left(\left(\Delta TC\ GS\text{-}25 - 31.5677906486595\right) * -0.0043314061661\right)\right)\right)
\end{aligned}
$$

(b) Probability of damage =

$$\frac{1}{\left(1 + \mathrm{Exp}\left(Lin[clean]\right)\right)}$$

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